United States Environmental Protection Agency
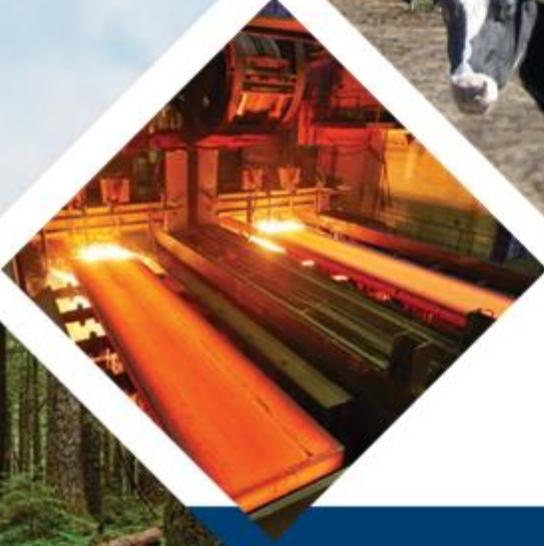
EPA 430-R-21-005

Inventory of
U.S. Greenhouse Gas Emissions and Sinks

1990-2019

HOW TO OBTAIN COPIES

You can electronically download this document on the U.S. EPA's homepage at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

All data tables of this document for the full time series 1990 through 2019, inclusive, will be made available with the final report published on April 14, 2021 at the internet site mentioned above.

FOR FURTHER INFORMATION

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For more information regarding climate change and greenhouse gas emissions, see the EPA web site at <https://www.epa.gov/ghgemissions>.

Acknowledgments

Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to fulfill annual existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Under Article 4 and decisions at the First, Second, Fifth and Nineteenth Conference of Parties, national inventories for UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, EPA conducts an annual public review and comment process for this document. The document was made available on the EPA Greenhouse Gas Emissions website and announced via Federal Register Notice for 30 days; comments received after the 30-day public comment period were accepted and will be considered for the next edition of this annual report. Public review of this year's report occurred from February 12 to March 15, 2021 and comments received were posted to the docket EPA-HQ-OAR-2021-0008. Responses to comments received will be posted to EPA's website within 2-4 weeks following publication of this report.

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Executive Summary

An emissions inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gases is essential for addressing climate change. This inventory adheres to both (1) a comprehensive and detailed set of methodologies for estimating national sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change.

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2]

As a signatory to the UNFCCC, consistent with Article 4[3] and decisions at the First, Second, Fifth, and Nineteenth Conference of Parties,[4] the United States is committed to submitting a national inventory of anthropogenic sources and sinks of greenhouse gases to the UNFCCC by April 15 of each year. The United States views this report, in conjunction with Common Reporting Format (CRF) reporting tables that accompany this report, as an opportunity to fulfill this annual commitment under the UNFCCC.

This executive summary provides the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2019. The structure of this report is consistent with the UNFCCC guidelines for inventory reporting, as discussed in Box ES-1.[5]

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[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See <http://unfccc.int>.

[3] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12) and subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. Article 4 states "Parties to the Convention, by ratifying, shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…" See <http://unfccc.int> for more information.

[4] See UNFCCC decisions 3/CP.1, 9/CP.2, 3/CP.5, and 24/CP.19 at <https://unfccc.int/documents>.

[5] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the UNFCCC requirement under Article 4.1 and related decisions to develop and submit annual national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory does not preclude alternative examinations, but rather this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP).[6] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[7] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and sinks (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in the Inventory.

Data presented in this Inventory report and EPA's Greenhouse Gas Reporting Program (GHGRP) are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., natural gas systems).

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[6] On October 30, 2009 the EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[7] See <http://www.epa.gov/ghgreporting> and <http://ghgdata.epa.gov/ghgp/main.do>.

ES.1 Background Information

Greenhouse gases absorb infrared radiation, thereby trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by humans include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2019, concentrations of these greenhouse gases have increased globally by 47, 167, and 23 percent, respectively (IPCC 2013; NOAA/ESRL 2021a, 2021b, 2021c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

Global Warming Potentials

Gases in the atmosphere can contribute to climate change both directly and indirectly. Direct effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations of the substance produce other greenhouse gases, when a gas influences the atmospheric lifetimes of other gases, and/or when a gas affects atmospheric processes that alter the radiative balance of the earth (e.g., affect cloud formation or albedo).[8] The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas.

The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2013). Therefore GWP-weighted emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[9, 10] Estimates for all gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are provided in the Trends chapter of this report and in the Common Reporting Format (CRF) tables that are also part of the submission to the UNFCCC.

UNFCCC reporting guidelines for national inventories require the use of GWP values from the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007).[11] All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission values using the AR4 GWP values versus the *IPCC Second Assessment Report* (SAR) (IPCC 1996), and the *IPCC Fifth Assessment Report* (AR5) (IPCC 2013) GWP values can be found in Chapter 1 and, in more detail, in Annex 6.1 of this report. The GWP values used in this report are listed below in Table ES-1.

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	25
N_2O	298
HFC-23	14,800
HFC-32	675
HFC-41	92
HFC-125	3,500

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[8] Albedo is a measure of the Earth's reflectivity and is defined as the fraction of the total solar radiation incident on a body that is reflected by it.

[9] Carbon comprises 12/44 of carbon dioxide by weight.

[10] One million metric ton is equal to 10^{12} grams or one teragram.

[11] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-43-10mee	1,640
HFC-245fa	1,030
HFC-365mfc	794
CF_4	7,390
C_2F_6	12,200
C_3F_8	8,830
$c\text{-}C_5F_8$	1.97
C_4F_{10}	8,860
$c\text{-}C_4F_8$	10,300
C_5F_{12}	9,160
C_6F_{14}	9,300
SF_6	22,800
NF_3	17,200
Other Fluorinated Gases	See Annex 6

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. See Annex 6 for additional information.
Source: IPCC (2007).

ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2019, total gross U.S. greenhouse gas emissions were 6,558.3 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.).[12] Total U.S. emissions have increased by 1.8 percent from 1990 to 2019, down from a high of 15.6 percent above 1990 levels in 2007. Emissions decreased from 2018 to 2019 by 1.7 percent (113.1 MMT CO_2 Eq.). Net emissions (including sinks) were 5,769.1 MMT CO_2 Eq. Overall, net emissions decreased 1.7 percent from 2018 to 2019 and decreased 13.0 percent from 2005 levels as shown in Table ES-2. The decline reflects the combined impacts of many long-term trends, including population, economic growth, energy market trends, technological changes including energy efficiency, and carbon intensity of energy fuel choices. Between 2018 and 2019, the decrease in total greenhouse gas emissions was largely driven by the decrease in CO_2 emissions from fossil fuel combustion. The decrease in CO_2 emissions from fossil fuel combustion was a result of a 1 percent decrease in total energy use and reflects a continued shift from coal to less carbon intensive natural gas and renewables in the electric power sector.

Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual percent changes, and relative change since 1990 for each year of the time series, and Table ES-2 provides information on trends in

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[12] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

gross U.S. greenhouse gas emissions and sinks for 1990 through 2019. Unless otherwise stated, all tables and figures provide total gross emissions and exclude the greenhouse gas fluxes from the Land Use, Land-Use Change, and Forestry (LULUCF) sector. For more information about the LULUCF sector see Section ES.3 Overview of Sector Emissions and Trends.

Figure ES-1: U.S. Greenhouse Gas Emissions by Gas
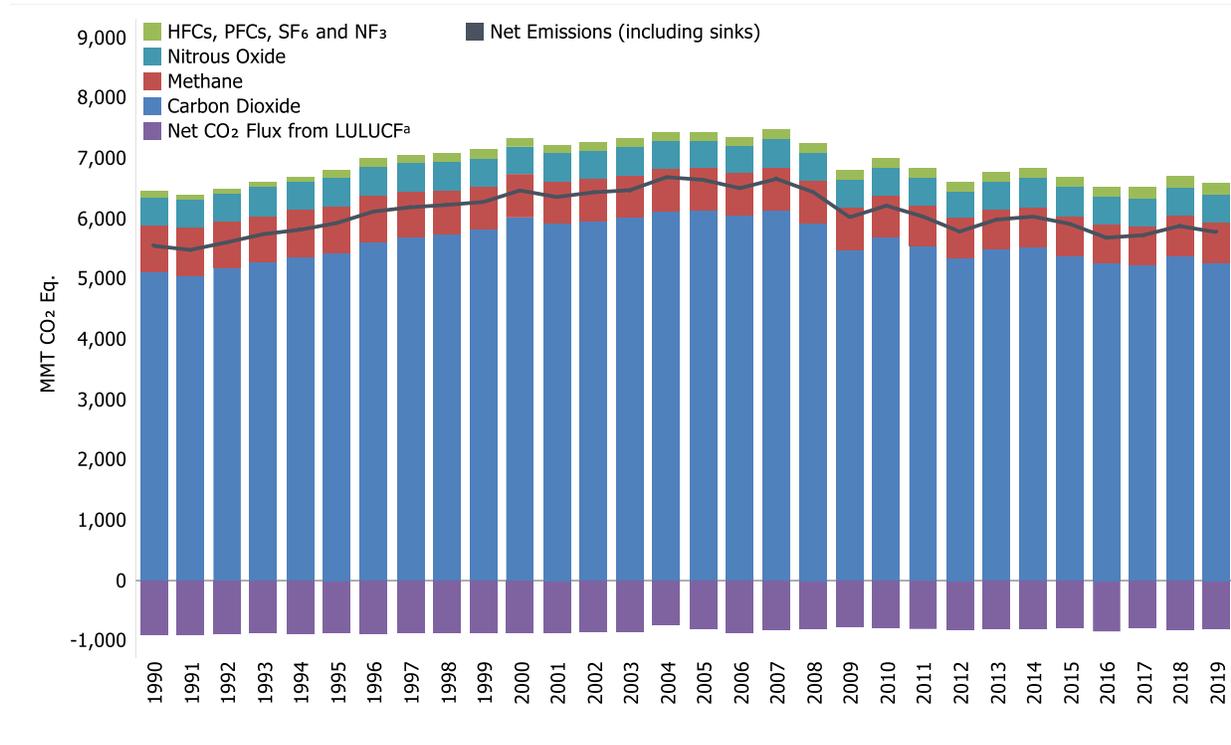
[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year
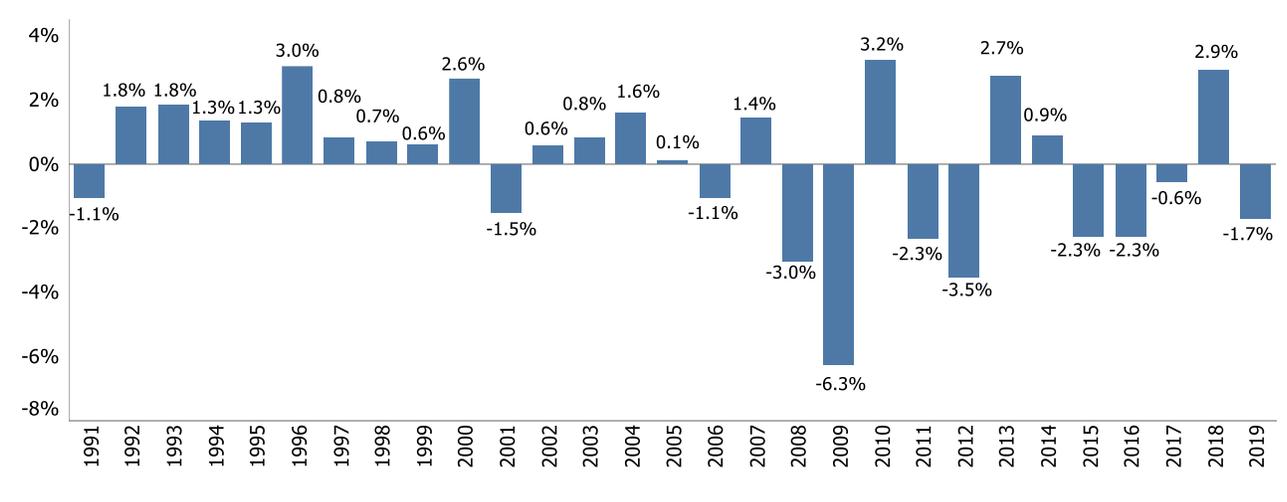
Figure ES-3: Change in Annual Gross U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0)
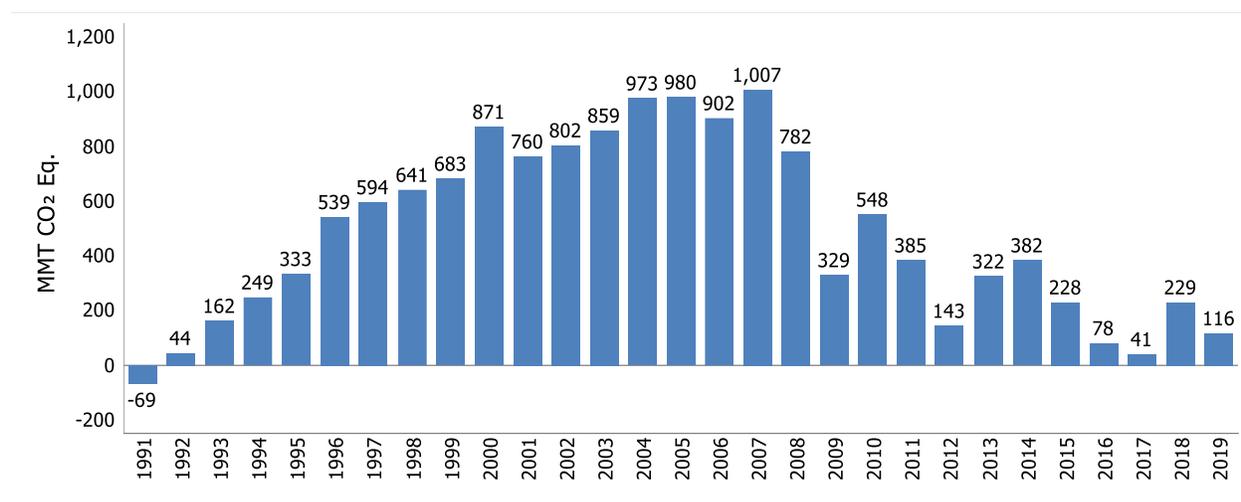
Box ES-2: Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and sink estimates in the Inventory are recalculated and revised to incorporate improved methods and/or data. The most common reason for recalculating U.S. greenhouse gas emission estimates is to update recent historical data. Changes in historical data are generally the result of changes in data supplied by other U.S. government agencies or organizations, as they continue to make refinements and improvements. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate.

Below are categories with recalculations resulting in an average change over the time series of greater than 10 MMT CO_2 Eq.

- *Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (CO_2)*
- *Wastewater Treatment (N_2O)*
- *Land Converted to Forest Land: Changes in all Ecosystem Carbon Stocks (CO_2)*
- *Non-Energy Use of Fuels (CO_2)*

In each Inventory, the results of all methodological changes and historical data updates are summarized in the Recalculations and Improvements chapter (Chapter 9). For more detailed descriptions of each recalculation including references for data, please see the respective source or sink category description(s) within the relevant report chapter (i.e., Energy chapter (Chapter 3), the Industrial Process and Product Use (IPPU) chapter (Chapter 4) the Agriculture chapter (Chapter 5), the Land Use, Land Use Change and Forestry (LULUCF) chapter (Chapter 6), and the Waste chapter (Chapter 7)). In implementing improvements, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when: available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; new inventory methods become available; and for correction of errors."

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO_2	**5,113.5**	**6,134.5**	**5,371.8**	**5,248.0**	**5,207.8**	**5,375.5**	**5,255.8**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Transportation	*1,469.1*	*1,858.6*	*1,719.2*	*1,759.9*	*1,782.4*	*1,816.6*	*1,817.2*
Electric Power	*1,820.0*	*2,400.1*	*1,900.6*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.0*
Industrial	*853.8*	*852.9*	*797.3*	*792.5*	*790.1*	*813.6*	*822.5*
Residential	*338.6*	*358.9*	*317.3*	*292.8*	*293.4*	*338.1*	*336.8*
Commercial	*228.3*	*227.1*	*244.6*	*231.6*	*232.0*	*245.7*	*249.7*
U.S. Territories	*21.7*	*55.9*	*29.2*	*26.0*	*24.6*	*24.6*	*24.6*
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	9.7	12.1	32.4	21.8	25.0	37.1	47.3
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	47.9	43.6	40.6	42.6	41.3
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Natural Gas Systems	32.0	25.2	29.1	30.1	31.2	33.9	37.2
Petrochemical Production	21.6	27.4	28.1	28.3	28.9	29.3	30.8
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Incineration of Waste	8.1	12.7	11.5	11.5	11.5	11.5	11.5
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4
Aluminum Production	6.8	4.1	2.8	1.3	1.2	1.5	1.9
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219.4*	*230.7*	*317.7*	*316.6*	*312.3*	*319.6*	*316.2*
International Bunker Fuels[b]	*103.5*	*113.2*	*110.9*	*116.6*	*120.1*	*122.1*	*116.1*
CH_4[c]	**776.9**	**686.1**	**651.5**	**642.4**	**648.4**	**655.9**	**659.7**
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Natural Gas Systems	186.9	164.2	149.8	147.3	148.7	152.5	157.6
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Manure Management	37.1	51.6	57.9	59.6	59.9	61.7	62.4
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Petroleum Systems	48.9	39.5	41.5	39.2	39.3	37.3	39.1
Wastewater Treatment	20.2	20.1	18.8	18.7	18.5	18.4	18.4

Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Stationary Combustion	8.6	7.8	8.5	7.9	7.6	8.5	8.7
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Mobile Combustion	6.4	4.0	2.6	2.5	2.5	2.4	2.4
Composting	0.4	1.9	2.1	2.3	2.4	2.3	2.3
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Petrochemical Production	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**452.7**	**455.8**	**468.2**	**450.8**	**446.3**	**459.2**	**457.1**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Wastewater Treatment	18.7	23.0	25.4	25.9	26.4	26.1	26.4
Stationary Combustion	25.1	34.4	30.5	30.0	28.4	28.2	24.9
Manure Management	14.0	16.4	17.5	18.1	18.7	19.4	19.6
Mobile Combustion	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Composting	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.2
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*
HFCs	**46.5**	**127.5**	**168.3**	**168.1**	**170.3**	**169.8**	**174.6**
Substitution of Ozone Depleting Substances[d]	0.2	107.3	163.6	164.9	164.7	166.0	170.5
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Electronics Industry	0.2	0.2	0.3	0.3	0.4	0.4	0.3
Magnesium Production and Processing	+	+	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.2**	**4.4**	**4.1**	**4.7**	**4.5**
Electronics Industry	2.8	3.3	3.1	2.9	2.9	3.0	2.7
Aluminum Production	21.5	3.4	2.1	1.4	1.1	1.6	1.8
Substitution of Ozone Depleting Substances	+	+	+	+	+	0.1	0.1
SF_6	**28.8**	**11.8**	**5.5**	**6.0**	**5.9**	**5.7**	**5.9**
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
Magnesium Production and Processing	5.2	2.7	1.0	1.1	1.0	1.0	0.9
Electronics Industry	0.5	0.7	0.7	0.8	0.7	0.8	0.8

NF$_3$	+	0.5	0.6	0.6	0.6	0.6	0.6
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Unspecified Mix of HFCs, PFCs, SF$_6$, and NF$_3$	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
Total Emissions (Sources)	6,442.7	7,423.0	6,671.1	6,520.3	6,483.3	6,671.4	6,558.3
LULUCF Emissions[c]	7.9	16.8	27.8	13.2	26.0	23.4	23.5
LULUCF CH$_4$ Emissions	5.0	9.3	16.6	7.7	15.3	13.8	13.8
LULUCF N$_2$O Emissions	3.0	7.5	11.3	5.5	10.6	9.7	9.7
LULUCF Carbon Stock Change[e]	(908.7)	(804.8)	(791.7)	(856.0)	(792.0)	(824.9)	(812.7)
LULUCF Sector Net Total[f]	(900.8)	(788.1)	(763.8)	(842.8)	(766.1)	(801.4)	(789.2)
Net Emissions (Sources and Sinks)	5,541.9	6,635.0	5,907.3	5,677.5	5,717.2	5,870.0	5,769.1

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.05 MMT CO$_2$ Eq.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH$_4$ and N$_2$O are reported separately from gross emissions totals. LULUCF emissions include the CH$_4$ and N$_2$O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH$_4$ emissions from *Land Converted to Coastal Wetlands*; and N$_2$O emissions from Forest Soils and Settlement Soils.

[d] Small amounts of PFC emissions also result from this source.

[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[f] The LULUCF Sector Net Total is the net sum of all LULUCF CH$_4$ and N$_2$O emissions to the atmosphere plus net C stock changes.

Figure ES-4 illustrates the relative contribution of the greenhouse gases to total U.S. emissions in 2019, weighted by global warming potential. The primary greenhouse gas emitted by human activities in the United States was CO$_2$, representing approximately 80.1 percent of total greenhouse gas emissions. The largest source of CO$_2$, and of overall greenhouse gas emissions, was fossil fuel combustion primarily from transportation and power generation. Methane emissions (CH$_4$) account for approximately 10.1 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management were the major sources of N$_2$O emissions. Ozone depleting substance substitute emissions and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions were primarily attributable to electronics manufacturing and primary aluminum production. Electrical transmission and distribution systems accounted for most sulfur hexafluoride (SF$_6$) emissions. The electronics industry is the only source of nitrogen trifluoride (NF$_3$) emissions.

Figure ES-4: 2019 U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO₂ Eq.)
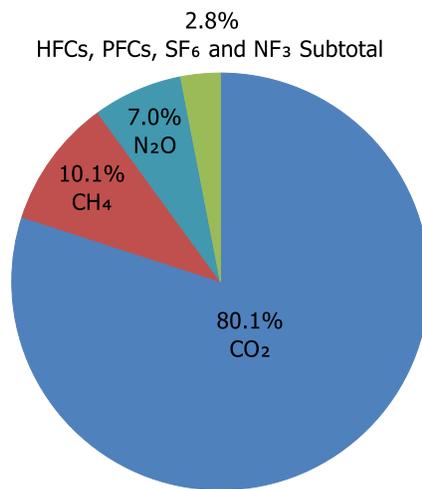
Overall, from 1990 to 2019, total emissions of CO_2 increased by 142.4 MMT CO_2 Eq. (2.8 percent), while total emissions of CH_4 decreased by 117.2 MMT CO_2 Eq. (15.1 percent) and emissions of N_2O increased by 4.5 MMT CO_2 Eq. (1.0 percent). During the same period, aggregate weighted emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) rose by 86.0 MMT CO_2 Eq. (86.3 percent). From 1990 to 2019, HFCs increased by 128.1 MMT CO_2 Eq. (275.4 percent), PFCs decreased by 19.8 MMT CO_2 Eq. (81.5 percent), SF_6 decreased by 22.9 MMT CO_2 Eq. (79.5 percent), and NF_3 increased by 0.6 MMT CO_2 Eq. (1,162.7 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6 and NF_3 are significant because many of these gases have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which, in aggregate, offset 12.4 percent of total emissions in 2019 (as reflected in Figure ES-1). The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, global carbon fluxes among these various reservoirs are roughly balanced.[13]

Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen approximately 47 percent (IPCC 2013; NOAA/ESRL 2021a), principally due to the combustion of fossil fuels for

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[13] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

energy. Globally, an estimated 33,513 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2018, of which the United States accounted for approximately 15 percent.[14]

Within the United States, fossil fuel combustion accounted for 92.4 percent of CO_2 emissions in 2019. Transportation was the largest emitter of CO_2 in 2019 followed by electric power generation. There are 25 additional sources of CO_2 emissions included in the Inventory (see Table ES-5). Although not illustrated in the Table ES-5, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass). See more on these emissions and removals in Table ES-5.

Figure ES-5: 2019 Sources of CO_2 Emissions
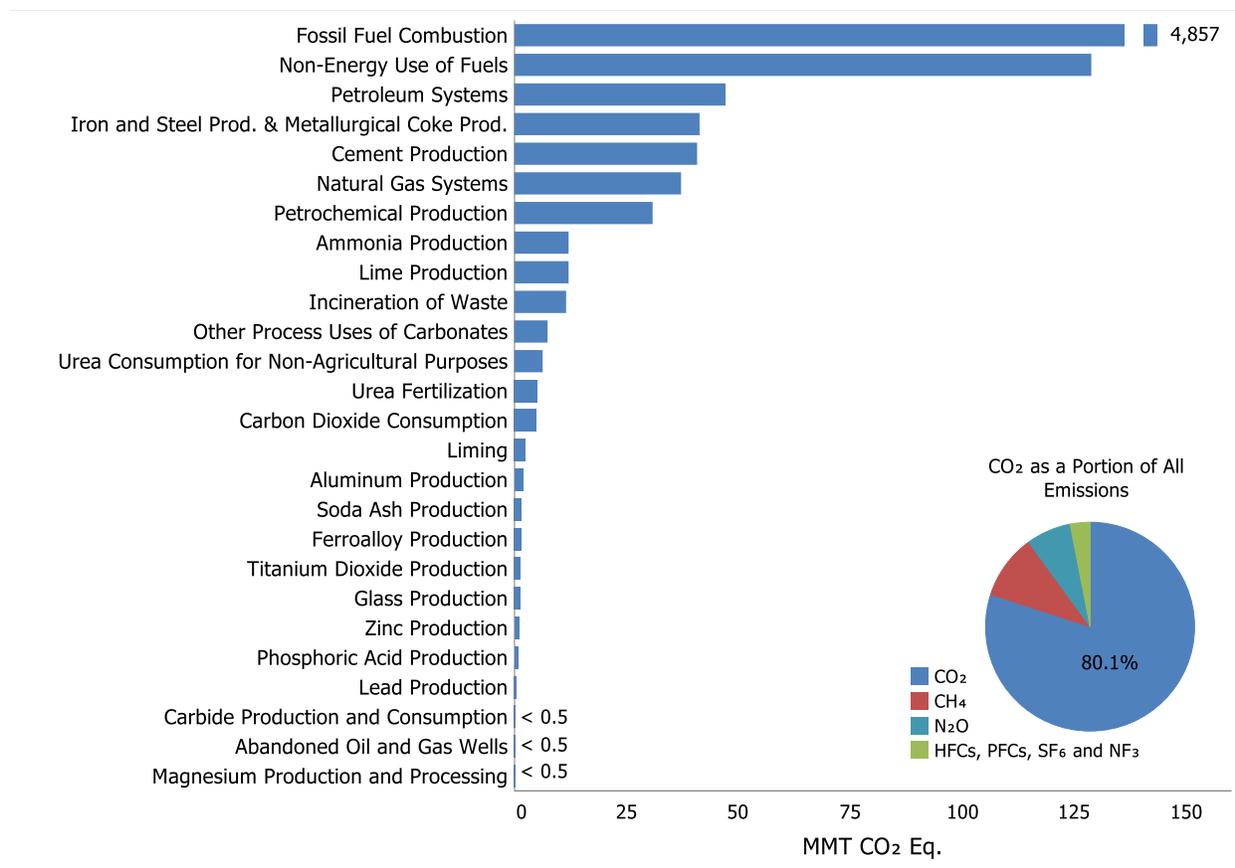
As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 76 percent of GWP-weighted total U.S. gross emissions across the time series. Between 1990 and 2019, CO_2 emissions from fossil fuel combustion increased from 4,731.5 MMT CO_2 Eq. to 4,856.7 MMT CO_2 Eq., a 2.6 percent total increase. Conversely, CO_2 emissions from fossil fuel combustion decreased by 896.8 MMT CO_2 Eq. from 2005 levels, a decrease of approximately 15.6 percent. From 2018 to 2019, these emissions decreased by 134.7 MMT CO_2 Eq. (2.7 percent).

Historically, changes in emissions from fossil fuel combustion have been the driving factor affecting U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. Important drivers include: (1) changes in demand for energy; and (2) a general decline in the carbon

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[14] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *CO_2 Emissions from Fossil Fuels Combustion Overview.* See <https://webstore.iea.org/co2-emissions-from-fuel-combustion-2020-highlights> (IEA 2020). The publication has not yet been updated to include complete global 2019 data.

intensity of fuels combusted for energy in recent years by non-transport sectors of the economy. Long-term factors affecting energy demand include population and economic trends, technological changes including energy efficiency, shifting energy fuel choices, and various policies at the national, state, and local level. In the short term, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives.

The five major fuel-consuming economic sectors are transportation, electric power, industrial, residential, and commercial. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four sectors, or "end-use" sectors, see Figure ES-6. Note that this Figure reports emissions from U.S. Territories as their own end-use sector due to incomplete data for their individual end-use sectors. Fossil fuel combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure ES-6: 2019 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
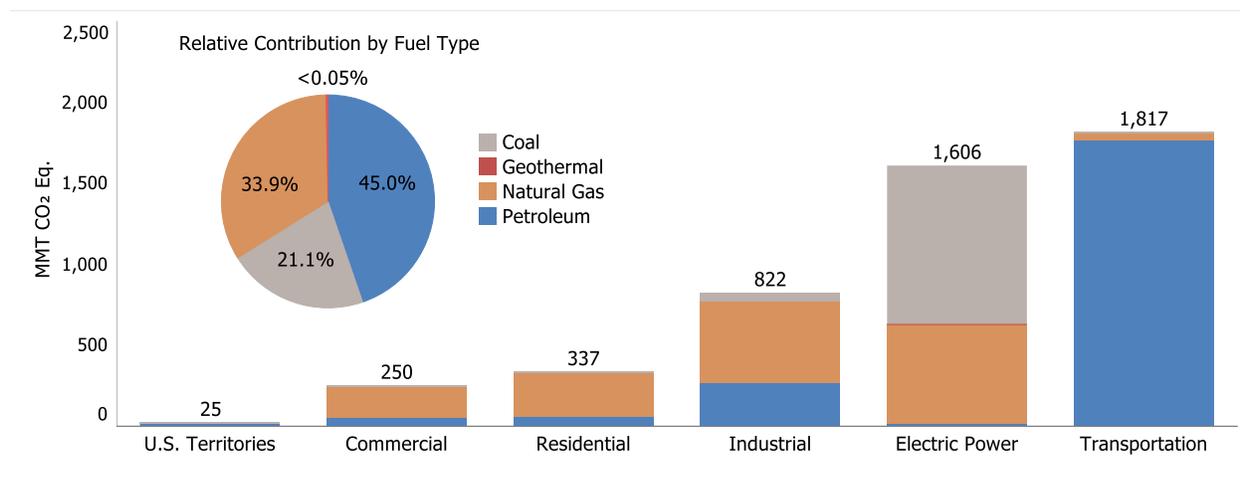
Figure ES-7 and Table ES-3 summarize CO_2 emissions from fossil fuel combustion by end-use sector including electric power emissions. For Figure ES-7 below, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use (i.e., indirect fossil fuel combustion). This method of distributing emissions assumes that each end-use sector uses electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electric power are also addressed separately after the end-use sectors are discussed.

Figure ES-7: 2019 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion
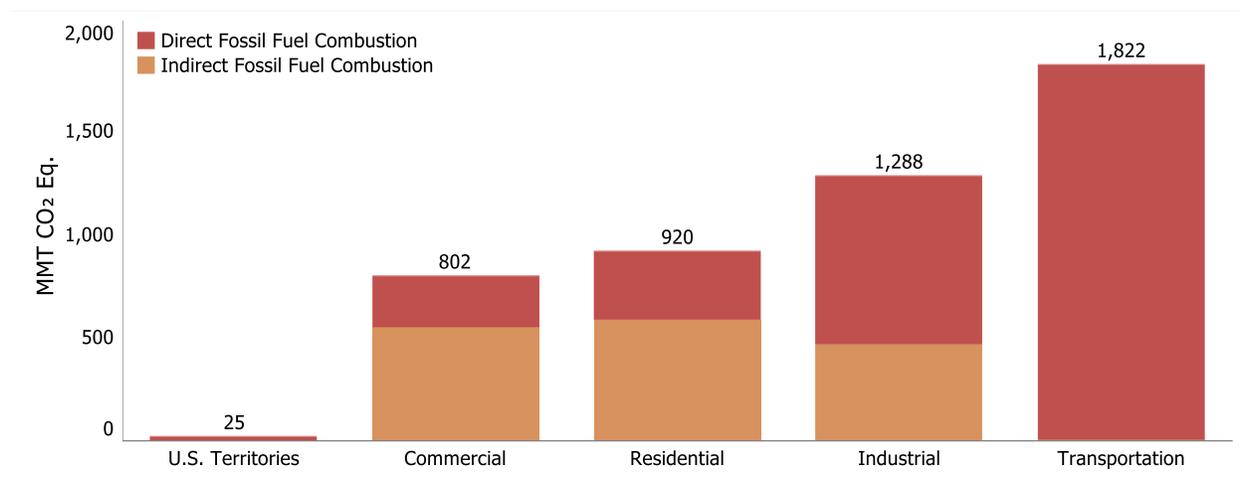
Table ES-3: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2015	2016	2017	2018	2019
Transportation	**1,472.2**	**1,863.4**	**1,723.5**	**1,764.1**	**1,786.8**	**1,821.2**	**1,821.9**
Combustion	1,469.1	1,858.6	1,719.2	1,759.9	1,782.4	1,816.6	1,817.2
Electricity	3.0	4.7	4.3	4.2	4.3	4.7	4.7
Industrial	**1,540.2**	**1,589.2**	**1,346.8**	**1,310.1**	**1,294.5**	**1,314.9**	**1,287.8**
Combustion	853.8	852.9	797.3	792.5	790.1	813.6	822.5
Electricity	686.4	736.3	549.5	517.6	504.4	501.3	465.3
Residential	**931.3**	**1,214.9**	**1,001.1**	**946.2**	**910.5**	**980.2**	**920.3**
Combustion	338.6	358.9	317.3	292.8	293.4	338.1	336.8
Electricity	592.7	856.0	683.8	653.5	617.1	642.1	583.5
Commercial	**766.0**	**1,030.1**	**907.6**	**865.2**	**838.2**	**850.6**	**802.1**
Combustion	228.3	227.1	244.6	231.6	232.0	245.7	249.7
Electricity	537.7	803.0	663.0	633.6	606.2	604.8	552.4
U.S. Territories[a]	**21.7**	**55.9**	**29.2**	**26.0**	**24.6**	**24.6**	**24.6**
Total	**4,731.5**	**5,753.5**	**5,008.3**	**4,911.5**	**4,854.5**	**4,991.4**	**4,856.7**
Electric Power	**1,820.0**	**2,400.1**	**1,900.6**	**1,808.9**	**1,732.0**	**1,752.9**	**1,606.0**

Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector and represent indirect fossil fuel combustion for each end-use sector. Totals may not sum due to independent rounding.

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

Transportation End-Use Sector. Transportation activities accounted for 37.5 percent of U.S. CO_2 emissions from fossil fuel combustion in 2019. The largest sources of transportation CO_2 emissions in 2019 were passenger cars (40.5 percent); freight trucks (23.6 percent); light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.2 percent); commercial aircraft (7.2 percent); pipelines (2.9 percent); other aircraft (2.4 percent); rail (2.2 percent); and ships and boats (2.1 percent). Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

In terms of the overall trend, from 1990 to 2019, total transportation CO_2 emissions increased due, in large part, to increased demand for travel. The number of vehicle miles traveled (VMT) by light-duty motor vehicles (i.e.,

passenger cars and light-duty trucks) increased 47.5 percent from 1990 to 2019,[15] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. While an increased demand for travel has led to increasing CO_2 emissions since 1990, improvements in average new vehicle fuel economy since 2005 has slowed the rate of increase of CO_2 emissions. Petroleum-based products supplied 95.1 percent of the energy consumed for transportation, with 56.5 percent being related to gasoline consumption in automobiles and other highway vehicles. Diesel fuel for freight trucks and jet fuel for aircraft, accounted for 24.3 and 13.3 percent, respectively. The remaining 0.9 percent of petroleum-based energy consumed for transportation was supplied by natural gas, residual fuel, aviation gasoline, and liquefied petroleum gases. The remaining 4.9 percent of energy consumed for transportation is associated with renewable fuels (i.e., biofuels).

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is used by industry, accounted for 27 percent of CO_2 emissions from fossil fuel combustion in 2019. Approximately 64 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. Total direct and indirect emissions from the industrial sector have declined by 16.4 percent since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19 and 17 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2019. The residential and commercial sectors relied heavily on electricity for meeting energy demands, with 63 and 69 percent, respectively, of their emissions attributable to electricity use for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Total direct and indirect emissions from the residential sector have decreased by 1 percent since 1990. Total direct and indirect emissions from the commercial sector have increased by 4.7 percent since 1990.

Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 31 percent of U.S. energy from fossil fuels and emitted 33 percent of the CO_2 from fossil fuel combustion in 2019. The type of energy source used to generate electricity is the main factor influencing emissions.[16] For example, some electricity is generated through non-fossil fuel options such as nuclear, hydroelectric, wind, solar, or geothermal energy. The mix of fossil fuels used also impacts emissions. The electric power sector is the largest consumer of coal in the United States. The coal used by electricity generators accounted for 93 percent of all coal consumed for energy in the United States in 2019.[17] However, the amount of coal and the percent of total electricity generation from coal has been decreasing over time. Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 28 percent in 2019.[18] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the thirty-year period to represent 34 percent of electric power generation in 2019. Wind and

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[15] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2019). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2019 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

[16] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[17] See Table 6.2 Coal Consumption by Sector of EIA (2020a).

[18] Values represent electricity *net* generation from the electric power sector. See Table 7.2b Electricity Net Generation: Electric Power Sector of EIA (2020a).

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solar generation (in kWh) represented 0.1 percent of electric power generation in 1990 and increased over the thirty-year period to represent 9 percent of electric power generation in 2019.

Across the time series, changes in electricity generation and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While CO_2 emissions from the electric power sector have decreased by approximately 12 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has significantly decreased– by 27 percent–during that same timeframe. This decoupling of the level of electric power generation and the resulting CO_2 emissions is shown in Figure ES-8.

Figure ES-8: Electric Power Generation and Emissions
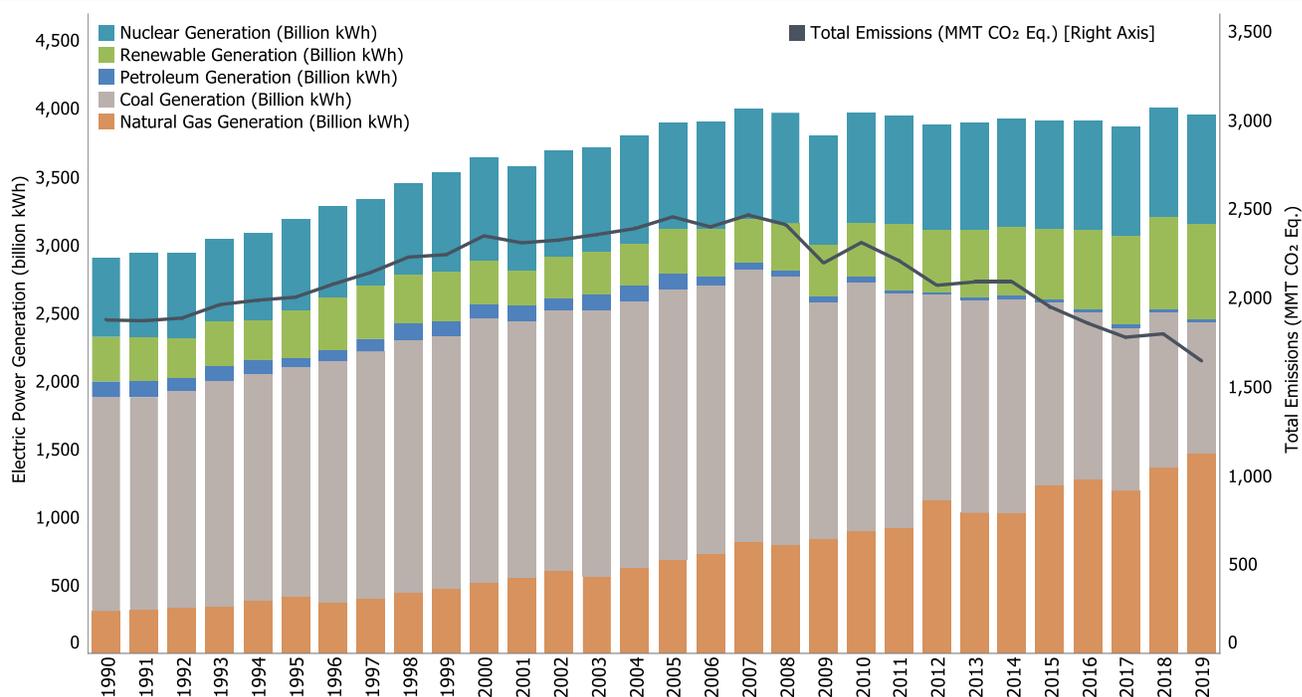
Other significant CO_2 trends included the following:

- Carbon dioxide emissions from natural gas and petroleum systems increased by 42.8 MMT CO_2 Eq. (102.4 percent) from 1990 to 2019. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.

- Carbon dioxide emissions from iron and steel production and metallurgical coke production have decreased by 63.4 MMT CO_2 Eq. (60.6 percent) from 1990 through 2019, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.

- Total C stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by approximately 10.6 percent between 1990 and 2019. This decrease was primarily due to a decrease in the rate of net C accumulation in forest C stocks and *Cropland Remaining Cropland,* as well as an increase in emissions from *Land Converted to Settlements*.

Methane Emissions

Methane (CH_4) is significantly more effective than CO_2 at trapping heat in the atmosphere–by a factor of 25 over a 100-year time frame based on the *IPCC Fourth Assessment Report* estimate (IPCC 2007). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 167 percent (IPCC 2013; NOAA/ESRL

2021b). Within the United States, the main anthropogenic sources of CH_4 include enteric fermentation from domestic livestock, natural gas systems, landfills, domestic livestock manure management, coal mining, and petroleum systems (see Figure ES-9).

Figure ES-9: 2019 Sources of CH_4 Emissions
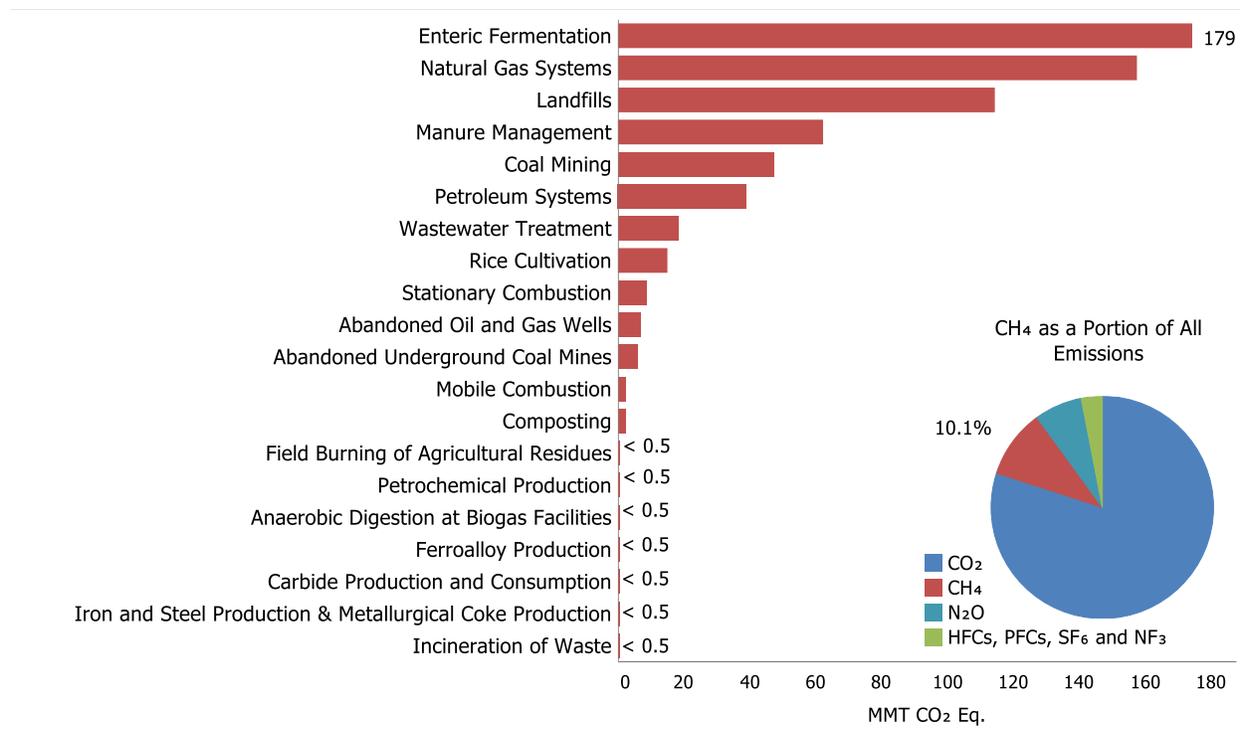
Note: Emissions of CH_4 from LULUCF are reported separately from gross emissions totals and are not included in Figure ES-9. Refer to Table ES-5 for a breakout of LULUCF emissions by gas.

Significant trends for the largest sources of U.S. CH_4 emissions include the following:

- Enteric fermentation was the largest anthropogenic source of CH_4 emissions in the United States. In 2019, enteric fermentation CH_4 emissions were 178.6 MMT CO_2 Eq. (27.1 percent of total CH_4 emissions), which represents an increase of 13.9 MMT CO_2 Eq. (8.4 percent) since 1990. This increase in emissions from 1990 to 2019 generally follows the increasing trends in cattle populations.

- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2019 with 157.6 MMT CO_2 Eq. of CH_4 emitted into the atmosphere. Those emissions have decreased by 29.3 MMT CO_2 Eq. (15.7 percent) since 1990. The decrease in CH_4 emissions is largely due to decreases in emissions from distribution, transmission, and storage. The decrease in distribution emissions is due to decreased emissions from pipelines and distribution station leaks, and the decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and equipment leaks).

- Landfills were the third largest anthropogenic source of CH_4 emissions in the United States (114.5 MMT CO_2 Eq.), accounting for 17.4 percent of total CH_4 emissions in 2019. From 1990 to 2019, CH_4 emissions from landfills decreased by 62.1 MMT CO_2 Eq. (35.2 percent), with small year-to-year increases. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings)

discarded in MSW landfills over the time series.[19] While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows.

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is nearly 300 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time frame (IPCC 2007). Since 1750, the global atmospheric concentration of N_2O has risen by approximately 23 percent (IPCC 2013; NOAA/ESRL 2021c). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, wastewater treatment, stationary fuel combustion, manure management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-10).

Figure ES-10: 2019 Sources of N_2O Emissions
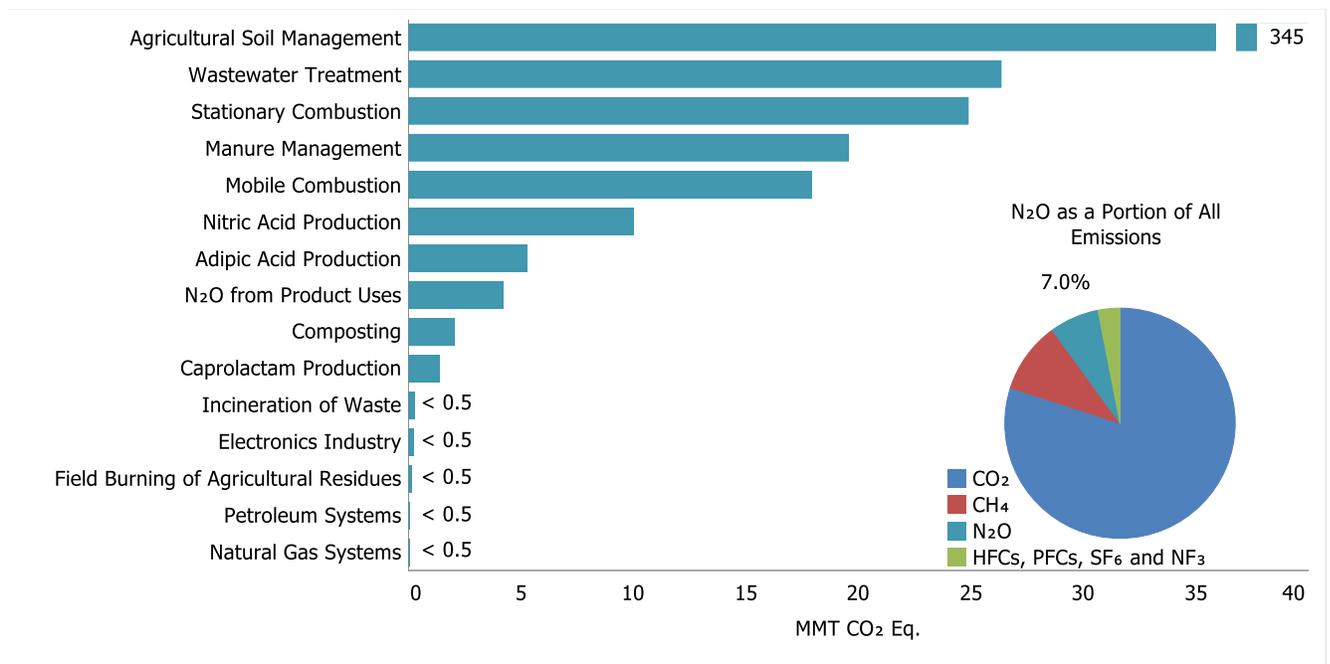
Note: Emissions of N_2O from LULUCF are reported separately from gross emissions totals and are not included in Figure ES-10. Refer to Table ES-5 for a breakout of LULUCF emissions by gas.

Significant trends for the largest sources of U.S. emissions of N_2O include the following:

- Agricultural soils accounted for 75.4 percent of N_2O emissions and 5.3 percent of total greenhouse gas emissions in the United States in 2019. Estimated emissions from this source in 2019 were 344.6 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2019, although overall emissions were 9.1 percent higher in 2019 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.

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[19] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

- Wastewater treatment, both domestic and industrial, accounted for 5.8 percent of N_2O emissions and 0.4 percent of total greenhouse gas emissions in the United States in 2019. Emissions from wastewater treatment increased by 41.0 percent (7.7 MMT CO_2 Eq.) since 1990. Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of growing U.S. population and protein consumption. Nitrous oxide emissions from industrial wastewater treatment sources, included for the first time in the current (i.e., 1990 to 2019) Inventory, fluctuated throughout the time series with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have increased since 2017.

- Nitrous oxide emissions from manure management accounted for 4.3 percent of N_2O emissions in 2019 and increased by 40.2 percent (5.6 MMT CO_2 Eq.) from 1990 to 2019. While the industry trend has been a shift toward liquid systems, driving down the emissions per unit of nitrogen excreted (dry manure handling systems have greater aerobic conditions that promote N_2O emissions), increases in specific animal populations have driven an increase in overall manure management N_2O emissions over the time series.

- Nitrous oxide emissions from mobile combustion decreased by 26.8 MMT CO_2 Eq. (59.8 percent) from 1990 to 2019, primarily as a result of national vehicle emissions standards and emission control technologies for on-road vehicles.

HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) are synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons do not deplete the stratospheric ozone layer and therefore have been used as alternatives under the Montreal Protocol on Substances that Deplete the Ozone Layer.

Perfluorocarbons (PFCs) are emitted from the production of electronics and aluminum and also (in smaller quantities) from their use as alternatives to ozone depleting substances. Sulfur hexafluoride (SF_6) is emitted from the production of electronics and magnesium and from the manufacturing and use of electrical transmission and distribution equipment. NF_3 is also emitted from electronics production. One HFC, HFC-23, is emitted during production of HCFC-22 and electronics (see Figure ES-11).

HFCs, PFCs, SF_6, and NF_3 are potent greenhouse gases. In addition to having very high global warming potentials, SF_6 and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2013).

Figure ES-11: 2019 Sources of HFCs, PFCs, SF$_6$, and NF$_3$ Emissions
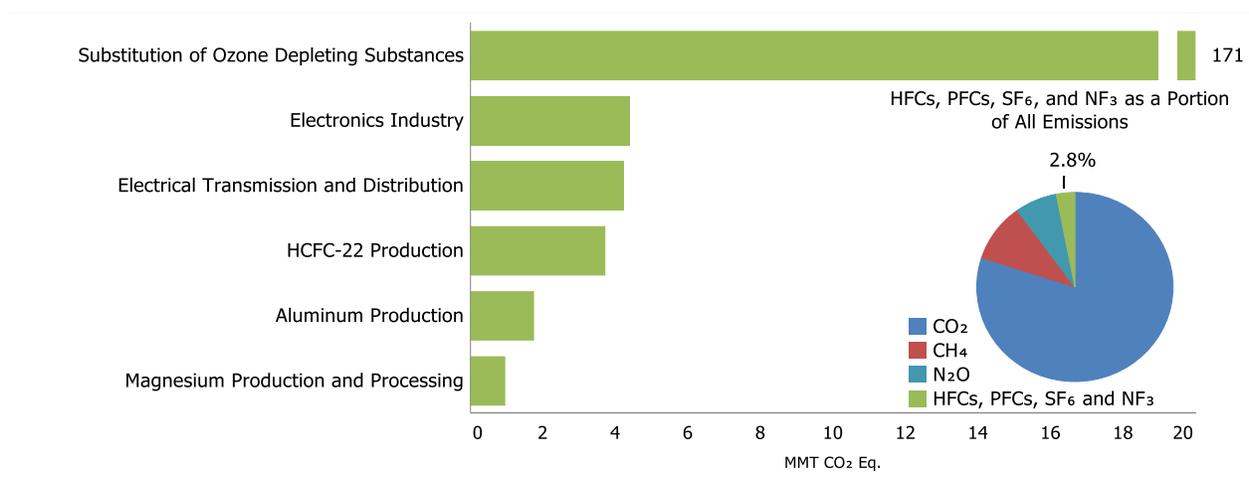
Some significant trends for the largest sources of U.S. HFC, PFC, SF$_6$, and NF$_3$ emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from their use as substitutes for ODS (e.g., chlorofluorocarbons [CFCs]) are the largest share of fluorinated emissions (92 percent) and have been consistently increasing, from small amounts in 1990 to 170.6 MMT CO$_2$ Eq. in 2019. This increase was in large part the result of efforts to phase out CFCs and other ODS in the United States.

- Emissions from HCFC-22 production were 3.7 MMT CO$_2$ Eq. in 2019, a 92 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by a reduction in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The emission rate was lowered by optimizing the production process and capturing much of the remaining HFC-23 for use or destruction.

- GWP-weighted PFC, HFC, SF$_6$, and NF$_3$ emissions from the electronics industry have increased by 23.7 percent from 1990 to 2019, reflecting the competing influences of industrial growth and the adoption of emission reduction technologies. Within that time span, emissions peaked at 9.0 MMT CO$_2$ Eq. in 1999, the initial year of EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, but have since declined to 4.4 MMT CO$_2$ Eq. in 2019 (a 51.3 percent decrease relative to 1999).

- Sulfur hexafluoride emissions from electric power transmission and distribution systems decreased by 81.7 percent (18.9 MMT CO$_2$ Eq.) from 1990 to 2019. There are two factors contributing to this decrease: (1) a sharp increase in the price of SF$_6$ during the 1990s and (2) a growing awareness of the environmental impact of SF$_6$ emissions through programs such as EPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems.

ES.3 Overview of Sector Emissions and Trends

Figure ES-12 and Table ES-4 aggregate emissions and sinks by the sectors defined by the UNFCCC reporting guidelines to promote comparability across countries. Over the thirty-year period of 1990 to 2019, total emissions from the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 66.7 MMT CO$_2$ Eq. (1.3 percent), 28.2 MMT CO$_2$ Eq. (8.1 percent), and 73.3 MMT CO$_2$ Eq. (13.2 percent), respectively. Emissions from the Waste sector decreased by 52.4 MMT CO$_2$ Eq. (24.2 percent). Over the same period, net C sequestration in the LULUCF sector decreased by 96.0 MMT CO$_2$ (10.6 percent decrease in total net C sequestration), while emissions from the LULUCF sector (i.e., CH$_4$ and N$_2$O) increased by 15.5 MMT CO$_2$ Eq. (196.1 percent).

Figure ES-12: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector
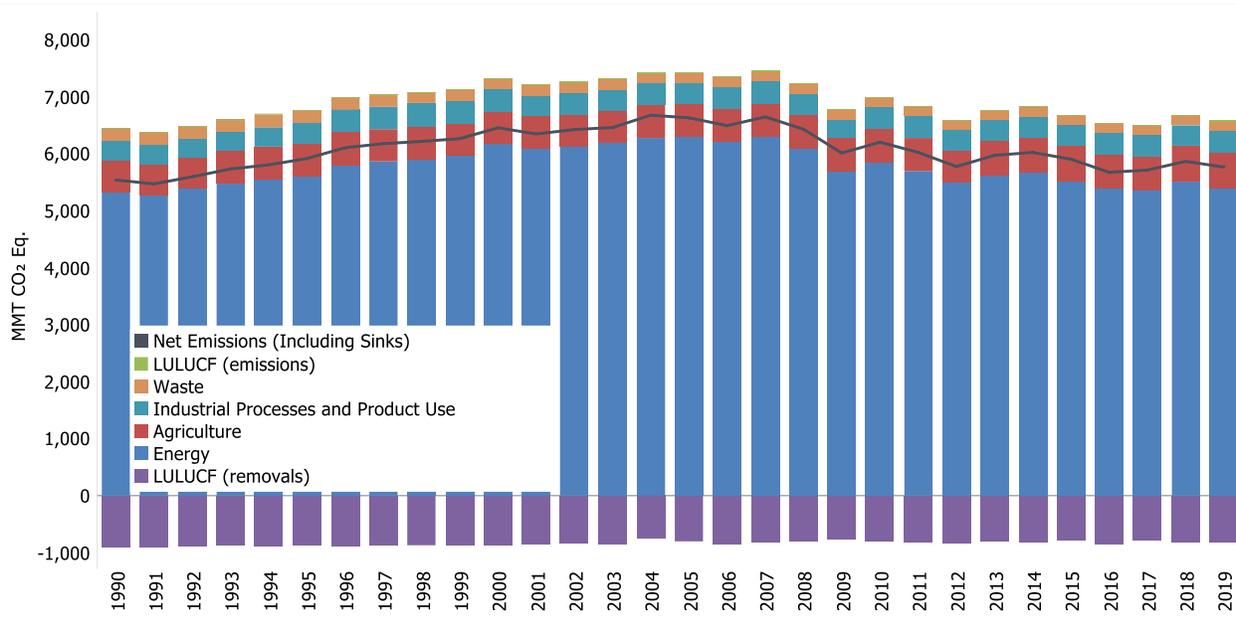
Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO₂ Eq.)

Chapter/IPCC Sector	1990	2005	2015	2016	2017	2018	2019
Energy	**5,325.6**	**6,302.3**	**5,519.8**	**5,390.9**	**5,351.0**	**5,518.1**	**5,392.3**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Natural Gas Systems	219.0	189.4	179.0	177.4	179.9	186.4	194.9
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	58.6	51.5	73.9	61.1	64.4	74.5	86.4
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Stationary Combustion	33.7	42.2	39.0	37.9	36.1	36.8	33.5
Mobile Combustion	51.1	45.5	24.4	23.4	22.3	21.3	20.3
Incineration of Waste	8.5	13.1	11.8	11.8	11.8	11.9	11.8
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Industrial Processes and Product Use	**345.6**	**365.7**	**375.4**	**368.0**	**367.7**	**371.3**	**373.7**
Substitution of Ozone Depleting Substances	0.2	107.3	163.6	164.9	164.7	166.1	170.6
Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	47.9	43.6	40.6	42.6	41.3
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Petrochemical Production	21.8	27.5	28.2	28.6	29.2	29.6	31.1
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Electronics Industry	3.6	4.8	5.0	5.0	4.9	5.1	4.6
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
N₂O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2

HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Aluminum Production	28.3	7.6	4.9	2.7	2.3	3.1	3.6
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Magnesium Production and Processing	5.2	2.7	1.1	1.2	1.1	1.1	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**555.3**	**577.1**	**616.1**	**604.4**	**605.5**	**621.0**	**628.6**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Manure Management	51.1	67.9	75.4	77.7	78.5	81.1	82.0
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Waste	**216.2**	**178.0**	**159.8**	**157.1**	**159.0**	**161.1**	**163.7**
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Wastewater Treatment	38.9	43.0	44.2	44.6	44.9	44.6	44.8
Composting	0.7	3.5	4.0	4.3	4.6	4.3	4.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
Total Emissions[a] (Sources)	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**
LULUCF Sector Net Total[b]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**
Forest land	(884.1)	(751.4)	(749.5)	(814.7)	(740.0)	(781.4)	(774.6)
Cropland	28.6	23.2	43.2	31.7	32.3	37.7	39.7
Grassland	2.2	(29.4)	(10.1)	(13.7)	(12.5)	(11.9)	(8.0)
Wetlands	(2.8)	(1.9)	(3.9)	(3.9)	(3.8)	(3.9)	(3.9)
Settlements	(44.7)	(28.5)	(43.5)	(42.2)	(42.1)	(42.0)	(42.4)
Net Emission (Sources and Sinks)[c]	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[a] Total emissions without LULUCF.

[b] The LULUCF Sector Net Total is the sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

[c] Net emissions with LULUCF.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2019. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.6 percent and 9.5 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 82.2 percent of total U.S. greenhouse gas emissions in 2019.

In 2019, approximately 80 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 20 percent came from other energy sources, such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-13).

Figure ES-13: 2019 U.S. Energy Consumption by Energy Source (Percent)
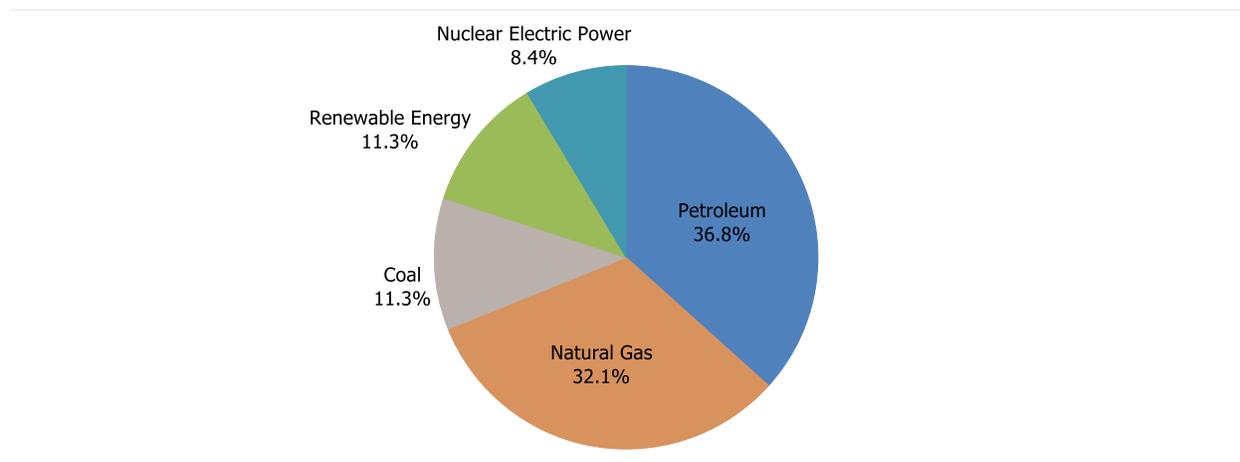
Pie chart:
- Nuclear Electric Power 8.4%
- Renewable Energy 11.3%
- Coal 11.3%
- Petroleum 36.8%
- Natural Gas 32.1%

Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter contains information on greenhouse gas emissions generated and emitted as the byproducts of non-energy-related industrial processes, which involve the chemical or physical transformation of raw materials and can release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, petrochemical production, lime production, ammonia production, nitric acid production, other process uses of carbonates (e.g., flue gas desulfurization), urea consumption for non-agricultural purposes, adipic acid production, HCFC-22 production, aluminum production, soda ash production and use, ferroalloy production, titanium dioxide production, caprolactam production, glass production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption. Most of these industries also emit CO_2 from fossil fuel combustion which, in line with IPCC sectoral definitions, is included in the Energy Sector.

This chapter also contains information on the release of HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds used in industrial manufacturing processes and by end-consumers (e.g., residential and mobile air conditioning). These industries include electronics industry, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by electronics industry and anesthetic and aerosol applications, and CO_2 is consumed and emitted through various end-use applications. In 2019, emissions resulting from use of the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) by end-consumers was the largest source of IPPU emissions and accounted for 170.6 MMT CO_2 Eq, or 45.6 percent of total IPPU emissions.

IPPU activities are responsible for 3.2, 0.1, and 4.6 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases such as HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 5.7 percent of U.S. greenhouse gas emissions in 2019.

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4, and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter).

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: agricultural soil management, enteric fermentation in domestic livestock, livestock manure management, rice cultivation, urea fertilization, liming, and field burning of agricultural residues.

In 2019, agricultural activities were responsible for emissions of 628.6 MMT CO_2 Eq., or 9.6 percent of total U.S. greenhouse gas emissions. Methane, N_2O, and CO_2 are greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented approximately 27.1 percent and 9.5 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2019. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2019, accounting for 75.4 percent of total N_2O emissions. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.1 percent of total CO_2 emissions from anthropogenic activities.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions and removals of CO_2 and emissions of CH_4 and N_2O from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals from unmanaged lands are considered to be natural.[20] The share of managed land in the U.S. is approximately 95 percent of total land included in the Inventory.[21] More information on the definition of managed land used in the Inventory is provided in Chapter 6.

Overall, the Inventory results show that managed land is a net sink for CO_2 (C sequestration). The primary drivers of fluxes on managed lands include forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings and food scraps, and activities that cause changes in C stocks in coastal wetlands. The main drivers for forest C sequestration include forest growth and increasing forest area (i.e., afforestation), as well as a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements,* which occurs predominantly from urban forests (i.e., Settlement Trees) and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest area, as well as long-term accumulation of yard trimmings and food scraps carbon in landfills.

The LULUCF sector in 2019 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.7 MMT CO_2 Eq. (Table ES-5).[22] This represents an offset of 12.3 percent of total (i.e., gross) greenhouse gas emissions in 2019. Emissions of CH_4 and N_2O from LULUCF activities in 2019 were 23.5 MMT CO_2 Eq. and represent 0.4 percent of total greenhouse gas emissions.[23] Between 1990 and 2019, total C sequestration in the LULUCF sector decreased by 10.6 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland,* as well as an increase in CO_2 emissions from *Land Converted to Settlements*. The overall net flux from LULUCF (i.e., net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 eq.) resulted in a removal of 789.2 MMT CO_2 Eq. in 2019.

Forest fires were the largest source of CH_4 emissions from the LULUCF sector in 2019, totaling 9.5 MMT CO_2 Eq. (379 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8 MMT CO_2 Eq. (153 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). *Land Converted to Wetlands* resulted in CH_4 emissions of 0.2 MMT CO_2 Eq (7 kt of CH_4). *Drained Organic Soils* and *Peatlands Remaining Peatlands* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

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[20] See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf>.

[21] The current land representation does not include land in U.S. Territories, but there are planned improvements to include these regions in future Inventories. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2 in Chapter 6 of this report.

[22] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[23] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Forest fires were also the largest source of N_2O emissions from the LULUCF sector in 2019, totaling 6.2 MMT CO_2 Eq. (21 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2019 totaled to 2.4 MMT CO_2 Eq. (8 kt of N_2O). Additionally, the application of synthetic fertilizers to forest soils in 2019 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and *Drained Organic Soils* resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (less than 0.5 kt of N_2O). *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Carbon dioxide removals from C stock changes are presented in Table ES-5 along with CH_4 and N_2O emissions for LULUCF source categories.

Table ES-5: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2015	2016	2017	2018	2019
Forest Land Remaining Forest Land	**(785.9)**	**(652.8)**	**(650.6)**	**(715.7)**	**(640.9)**	**(682.4)**	**(675.5)**
Changes in Forest Carbon Stocks[a]	(787.6)	(661.5)	(671.4)	(721.9)	(659.7)	(698.6)	(691.8)
Non-CO_2 Emissions from Forest Fires[b]	1.5	8.2	20.3	5.6	18.3	15.7	15.7
N_2O Emissions from Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.2)**	**(98.7)**	**(98.9)**	**(99.0)**	**(99.1)**	**(99.1)**	**(99.1)**
Changes in Forest Carbon Stocks[e]	(98.2)	(98.7)	(98.9)	(99.0)	(99.1)	(99.1)	(99.1)
Cropland Remaining Cropland	**(23.2)**	**(29.0)**	**(12.8)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)	(29.0)	(12.8)	(22.7)	(22.3)	(16.6)	(14.5)
Land Converted to Cropland	**51.8**	**52.2**	**56.1**	**54.4**	**54.6**	**54.3**	**54.2**
Changes in all Ecosystem Carbon Stocks[f]	51.8	52.2	56.1	54.4	54.6	54.3	54.2
Grassland Remaining Grassland	**8.5**	**10.7**	**13.8**	**10.4**	**11.9**	**12.3**	**15.1**
Changes in Mineral and Organic Soil Carbon Stocks	8.3	10.0	13.1	9.8	11.3	11.7	14.5
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.7	0.7	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(6.2)**	**(40.1)**	**(23.9)**	**(24.0)**	**(24.4)**	**(24.1)**	**(23.2)**
Changes in all Ecosystem Carbon Stocks[f]	(6.2)	(40.1)	(23.9)	(24.0)	(24.4)	(24.1)	(23.2)
Wetlands Remaining Wetlands	**(3.5)**	**(2.6)**	**(4.1)**	**(4.1)**	**(4.0)**	**(4.0)**	**(4.0)**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.8	0.7	0.8	0.8	0.8
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands	**0.7**	**0.7**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Changes in Biomass, DOM, and Soil Carbon Stocks	0.4	0.4	(0.1)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(123.7)**	**(121.5)**	**(121.4)**	**(121.2)**	**(121.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	15.7	16.0	16.0	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(130.4)	(129.8)	(129.8)	(129.8)	(129.8)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(11.1)	(10.0)	(9.8)	(9.8)	(10.2)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.2	2.3	2.4	2.4

Land Converted to Settlements	**62.9**		**85.0**		**80.1**	**79.4**	**79.3**	**79.3**	**79.2**
Changes in all Ecosystem Carbon Stocks[f]	62.9		85.0		80.1	79.4	79.3	79.3	79.2
LULUCF Carbon Stock Change[i]	**(908.7)**		**(804.8)**		**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
LULUCF Emissions[j]	**7.9**		**16.8**		**27.8**	**13.2**	**26.0**	**23.4**	**23.5**
LULUCF CH$_4$ Emissions	5.0		9.3		16.6	7.7	15.3	13.8	13.8
LULUCF N$_2$O Emissions	3.0		7.5		11.3	5.5	10.6	9.7	9.7
LULUCF Sector Net Total[k]	**(900.8)**		**(788.1)**		**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH$_4$ and N$_2$O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[g] Estimates include CH$_4$ and N$_2$O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland.*

[h] Estimates include N$_2$O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements* because it is not possible to separate the activity data at this time.

[i] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH$_4$ and N$_2$O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH$_4$ emissions from *Land Converted to Coastal Wetlands*; and N$_2$O emissions from Forest Soils and Settlement Soils.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH$_4$ and N$_2$O emissions to the atmosphere plus net carbon stock changes in units of MMT CO$_2$ Eq.

Waste

The Waste chapter contains emissions from waste management activities (except incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions from waste management activities, generating 114.5 MMT CO$_2$ Eq. and accounting for 69.9 percent of total greenhouse gas emissions from waste management activities, and 17.4 percent of total U.S. CH$_4$ emissions.[24] Additionally, wastewater treatment generated emissions of 44.8 MMT CO$_2$ Eq. and accounted for 27.3 percent of total Waste sector greenhouse gas emissions, 2.8 percent of U.S. CH$_4$ emissions, and 5.8 percent of U.S. N$_2$O emissions in 2019. Emissions of CH$_4$ and N$_2$O from composting are also accounted for in this chapter, generating emissions of 2.3 MMT CO$_2$ Eq. and 2.0 MMT CO$_2$ Eq., respectively. Anaerobic digestion at biogas facilities generated CH$_4$ emissions of 0.2 MMT CO$_2$ Eq., accounting for 0.1 percent of emissions from the waste sector. Overall, emission sources accounted for in the Waste chapter generated 163.7 MMT CO$_2$ Eq., or 2.5 percent of total U.S. greenhouse gas emissions in 2019.

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[24] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land-Use, Land-Use Change, and Forestry chapter of the Inventory report.

ES.4 Other Information

Emissions by Economic Sector

Throughout the Inventory of U.S. Greenhouse Gas Emissions and Sinks report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC: Energy; IPPU; Agriculture; LULUCF; and Waste. It is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. For more information on trends in the Land use, Land Use Change and Forestry sector, see section ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks.

Figure ES-14 shows the trend in emissions by economic sector from 1990 to 2019, and Table ES-6 summarizes emissions from each of these economic sectors.

Figure ES-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors
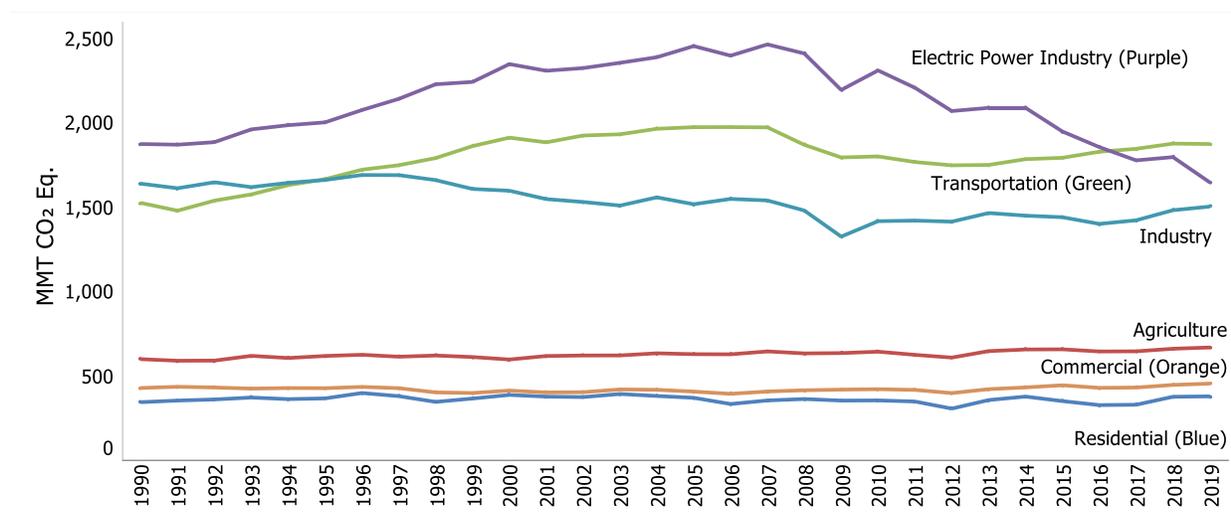
Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table ES-6: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO$_2$ Eq.)

Economic Sectors	1990	2005	2015	2016	2017	2018	2019
Transportation	1,526.6	1,975.6	1,794.1	1,830.0	1,847.3	1,878.2	1,875.7
Electric Power Industry	1,875.7	2,456.3	1,950.0	1,857.6	1,778.9	1,798.0	1,648.1
Industry	1,640.7	1,518.8	1,441.6	1,402.2	1,423.4	1,483.3	1,504.8
Agriculture	600.2	629.7	658.5	645.8	646.6	662.0	669.5
Commercial	429.2	407.9	445.4	430.1	431.9	447.3	455.3
Residential	345.1	371.0	351.5	327.8	329.9	377.3	379.5
U.S. Territories	25.2	63.7	30.0	26.8	25.4	25.4	25.4
Total Emissions (Sources)	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**
LULUCF Sector Net Total[a]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**
Net Emissions (Sources and Sinks)	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

[a] The LULUCF Sector Net Total is the net sum of all LULUCF CH$_4$ and N$_2$O emissions to the atmosphere plus net carbon stock changes.

Using this categorization, emissions from transportation activities, in aggregate, accounted for the largest portion (28.6 percent) of total U.S. greenhouse gas emissions in 2019. Electric power accounted for the second largest portion (25.1 percent) of U.S. greenhouse gas emissions in 2019, while emissions from industry accounted for the third largest portion (22.9 percent). Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 23.3 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.2 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for 6.9 percent and 5.8 percent of emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-7 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity for each end-use sector (EIA 2020a and Duffield 2006).[25] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity use are distributed among these end-use sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29.7 percent and 28.7 percent, respectively) in 2019. The commercial and residential sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2019 (15.6 and 14.9 percent, respectively). Emissions from the commercial and residential sectors increase substantially when emissions from electricity use are included, due to their relatively large share of electricity use for energy (e.g., lighting, cooling, appliances). In all sectors except agriculture, CO_2 accounts for more than 79.0 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Figure ES-15 shows the trend in these emissions by sector from 1990 to 2019.

Table ES-7: U.S. Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2015	2016	2017	2018	2019
Industry	2,313.1	2,234.1	1,964.2	1,894.6	1,902.7	1,958.3	1,947.2
Transportation	1,529.8	1,980.4	1,798.4	1,834.3	1,851.8	1,883.0	1,880.6
Commercial	983.4	1,229.8	1,125.7	1,080.8	1,054.5	1,067.8	1,022.3
Residential	956.0	1,247.1	1,053.1	998.9	963.7	1,035.9	978.3
Agriculture	635.3	668.0	699.7	684.9	685.3	701.1	704.6
U.S. Territories	25.2	63.7	30.0	26.8	25.4	25.4	25.4
Total Emissions (Sources)	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**
LULUCF Sector Net Total[a]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**
Net Emissions (Sources and Sinks)	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**

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[25] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals
    may not sum due to independent rounding. Parentheses indicate negative values or sequestration.
ª The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon
    stock changes.

Figure ES-15: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors
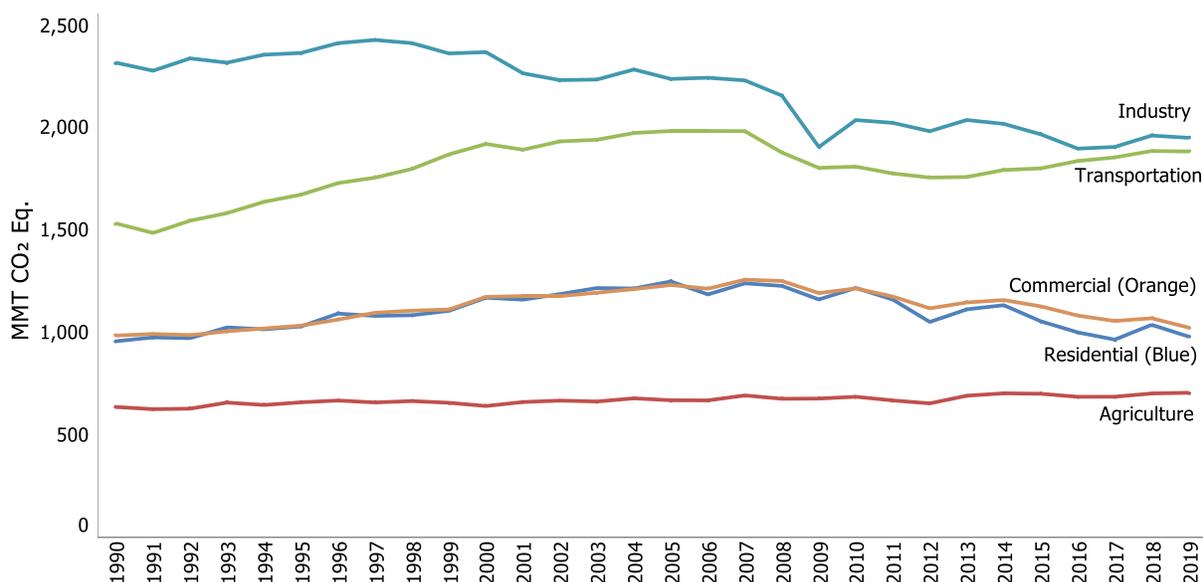
Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Box ES-3: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

Table ES-8 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use and fossil fuel consumption, and overall gross domestic product (GDP), and national population (see Figure ES-16). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.8percent since 2005. Fossil fuel consumption has also decreased at a slower rate than emissions since 2005, while total energy use, GDP, and national population continued to increase.

Table ES-8: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2015	2016	2017	2018	2019	Avg. Annual Growth Rate Since 1990ª	Avg. Annual Growth Rate Since 2005ª
Greenhouse Gas Emissionsᵇ	100	115	104	101	101	104	102	0.1%	-0.8%
Energy Useᶜ	100	119	116	116	116	120	119	0.6%	0.0%
GDPᵈ	100	159	186	189	194	200	204	2.5%	1.8%

Population[e]	100	118	128	129	130	131	132	1.0%	0.8%

[a] Average annual growth rate.
[b] GWP-weighted values.
[c] Energy content-weighted values (EIA 2020a).
[d] GDP in chained 2009 dollars (BEA 2020).
[e] U.S. Census Bureau (2020).

Figure ES-16: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)
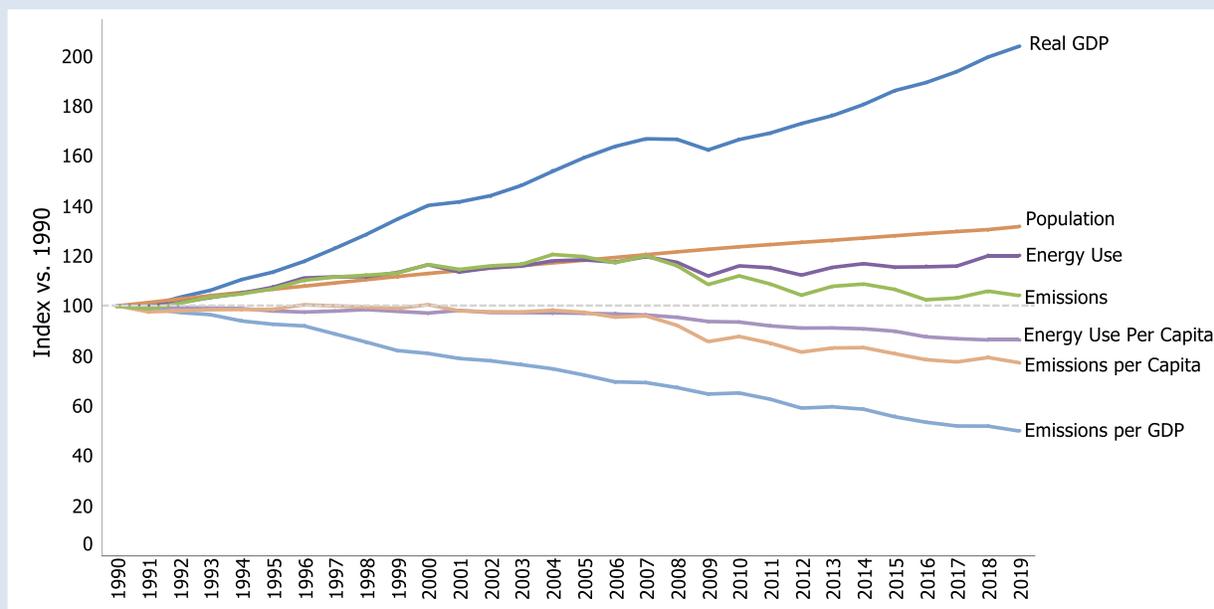
Source: BEA (2019), U.S. Census Bureau (2020), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[26] A key category analysis identifies priority source or sink categories for focusing efforts to improve overall Inventory quality. In addition, a qualitative review of key categories and non-key categories can also help identify additional source and sink categories to consider for improvement efforts, including reducing uncertainty.

Figure ES-17 presents the key categories identified by Approach 1 and Approach 2 level assessments including the LULUCF sector for 2019. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude. An Approach 2 level assessment incorporates the results of the uncertainty analysis for each category and identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude.

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[26] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html>.

For a complete list of key categories and more information regarding the overall key category analysis, including approaches accounting for the influence of trends of individual source and sink categories, see the Introduction chapter, Section 1.5 – Key Categories and Annex 1.

Figure ES-17: 2019 Key Categories[a]
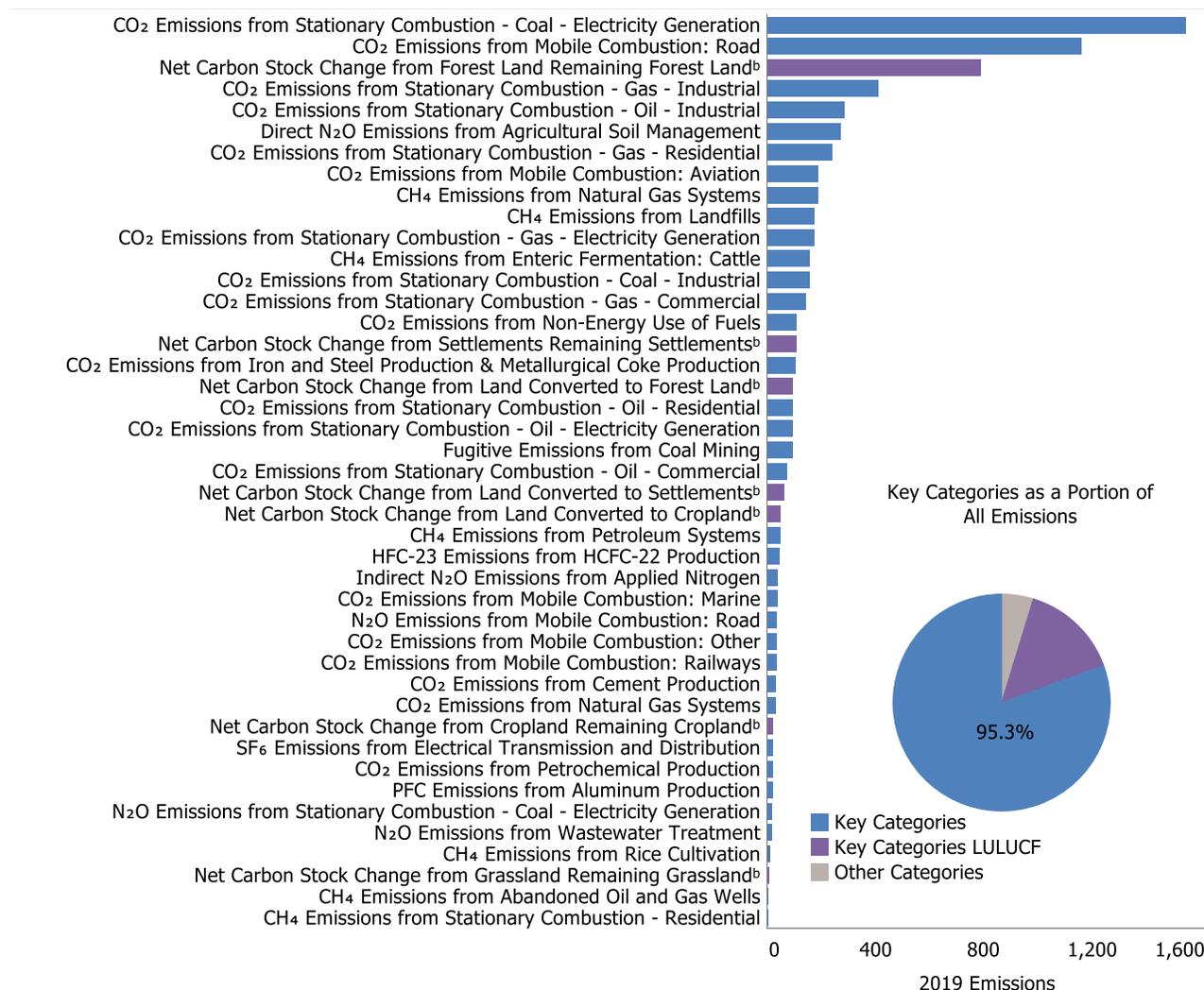
[a] For a complete list of key categories and detailed discussion of the underlying key category analysis, see Annex 1. Bars indicate key categories identified using Approach 1 and Approach 2 level assessment including the LULUCF sector.

[b] The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-5 for a breakout of emissions and removals for LULUCF by gas and source/sink category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency, and usability of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the U.S. Inventory QA/QC plan for the Inventory, and the UNFCCC reporting guidelines and *2006 IPCC Guidelines*. The QA process includes expert and public reviews for both the Inventory estimates and the Inventory report.

Box ES-4: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC.[27] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community on ambient measurement and remote sensing techniques to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[28] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used in a manner consistent with this Inventory report's transparency of its calculation methodologies, and the ability of these techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

In an effort to improve the ability to compare the national-level greenhouse gas inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization. The gridded inventory is designed to be consistent with the 1990 to 2014 U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates for the year 2012, which presents national totals for different source types.[29] This gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete inventory of greenhouse gas emissions and removals because they help to inform and prioritize inventory improvements. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories. In addition to quantitative uncertainty assessments, a qualitative discussion of uncertainty is presented for each source and sink category identifying specific factors affecting the uncertainty surrounding the estimates provided in accordance with UNFCCC reporting guidelines. Some of the current estimates, such as those for CO_2 emissions from energy-related combustion activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related combustion activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel, and for the United States, the uncertainties associated with estimating those factors is believed to be relatively small. For some other categories of emissions, however, inherent variability or a lack of data increases the uncertainty or systematic error associated with the estimates presented. Finally, an analysis is conducted to assess uncertainties associated with the overall emissions, sinks and trends estimates. The overall uncertainty surrounding total net greenhouse gas emissions is estimated to be -6 to + 6 percent in 1990 and -5 to +5 percent in 2019. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -2 to +5 percent in 1990 and -2 to +4 percent in 2019.

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[27] See <http://www.ipcc-nggip.iges.or.jp/public/index.html>.

[28] See <http://www.ipcc-nggip.iges.or.jp/meeting/pdfiles/1003_Uncertainty%20meeting_report.pdf>.

[29] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2019. A summary of these estimates is provided in Table 2-1 and Table 2-2 by gas and source category in the Trends in Greenhouse Gas Emissions chapter. The emission estimates in these tables are presented on both a full mass basis and on a global warming potential (GWP) weighted basis[1] in order to show the relative contribution of each gas to global average radiative forcing. This report also discusses the methods and data used to calculate these emission estimates.

In 1992, the United States signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2,3]

As a signatory to the UNFCCC, consistent with Article 4[4] and decisions at the First, Second, Fifth, and Nineteenth Conference of Parties,[5] the U.S. is committed to submitting a national inventory of anthropogenic sources and sinks of greenhouse gases to the UNFCCC by April 15 of each year. The United States views this report, in conjunction with Common Reporting Format (CRF) reporting tables that accompany this report, as an opportunity to fulfill this annual commitment under the UNFCCC.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific,

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[1] More information provided in the Global Warming Potentials section of this chapter on the use of *IPCC Fourth Assessment Report* (AR4) GWP values.

[2] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[3] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (UNEP/WMO 2000). See <http://unfccc.int>.

[4] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12) and subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. Article 4 states "Parties to the Convention, by ratifying, shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…" See <http://unfccc.int> for more information.

[5] See UNFCCC decisions 3/CP.1, 9/CP.2, 3/CP.5, and 24/CP.19 at https://unfccc.int/documents.

technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2014). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries collaborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and the *IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry* further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines*. In 2006, the IPCC accepted the *2006 Guidelines for National Greenhouse Gas Inventories* at its Twenty-Fifth Session (Mauritius, April 2006). The *2006 IPCC Guidelines* built upon the previous bodies of work and include new sources and gases, "…as well as updates to the previously published methods whenever scientific and technical knowledge have improved since the previous guidelines were issued." The UNFCCC adopted the *2006 IPCC Guidelines* as the standard methodological approach for Annex I countries and encouraged countries to gain experience in using the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). The IPCC has recently released the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* to clarify and elaborate on the existing guidance in the *2006 IPCC Guidelines*, along with providing updates to default values of emission factors and other parameters based on updated science. This report does make use of both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the Inventory. For more information on specific uses see Section 1.4 of this chapter on Methodology and Data Sources.

Overall, this Inventory of anthropogenic greenhouse gas emissions and sinks provides a common and consistent mechanism through which Parties to the UNFCCC can estimate emissions and compare the relative contribution of individual sources, gases, and nations to climate change. The Inventory provides a national estimate of sources and sinks for the United States, including all states, the District of Columbia and U.S. Territories.[6] The structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2014) for Parties included in Annex I of the Convention.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the UNFCCC requirement under Article 4.1 and decision 24/CP.19 to develop and submit annual national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory does not preclude alternative examinations, but rather this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and

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[6] U.S. Territories include American Samoa, Guam, Commonwealth of the Northern Mariana Islands, Puerto Rico, U.S. Virgin Islands, and other U.S. Pacific Islands which are not permanently inhabited such as Wake Island. See <https://www.usgs.gov/faqs/how-are-us-states-territories-and-commonwealths-designated-geographic-names-information-system?qt-news_science_products=0#qt-news_science_products>.

industrial gases through its Greenhouse Gas Reporting Program (GHGRP).[7] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[8] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and sinks (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in the Inventory.

Data presented in this Inventory report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., natural gas systems).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (NOAA 2017). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2013). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect and a negative number represents a cooling effect (IPCC 2013). IPCC concluded in its most recent scientific assessment report that it is extremely likely that human influences have been the dominant cause of warming since the mid-20th century (IPCC 2013).

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[7] On October 30, 2009 the EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[8] See <http://www.epa.gov/ghgreporting> and <http://ghgdata.epa.gov/ghgp/main.do>.

As concentrations of greenhouse gases continue to increase in from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 1.8 degrees Fahrenheit from 1901 to 2016 (USGCRP 2017). The last three decades have each been the warmest decade successively at the Earth's surface since 1850 (IPCC 2013). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase from 0.5 to 8.6 degrees Fahrenheit above 1986 through 2005 levels by the end of this century, depending on future emissions and the responsiveness of the climate system (IPCC 2013).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[9] the U.S. Global Change Research Program (USGCRP),[10] and the National Academies of Sciences, Engineering, and Medicine (NAS).[11]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2013).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in national greenhouse gas inventories.[12] Some other fluorine-containing halogenated substances— hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs, including CH_4) and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorb sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation

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[9] See <http://www.ipcc.ch/report/ar5>.

[10] See <https://science2017.globalchange.gov/>.

[11] See <http://nas-sites.org/americasclimatechoices/>.

[12] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

patterns. Comparatively, however, while the understanding of aerosols has increased in recent years, they still account for the largest contribution to uncertainty estimates in global energy budgets (IPCC 2013).

Carbon dioxide, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.700 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	411 ppm[a]	1.866 ppm[b]	0.331 ppm[c]	9.9 ppt[d]	79 ppt[e]
Rate of concentration change	2.3 ppm/yr[f]	7 ppb/yr[f,g]	0.8 ppb/yr[f]	0.27 ppt/yr[f]	0.7 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	12.4[i]	121[i]	3,200	50,000

[a] The atmospheric CO_2 concentration is the 2019 annual average at the Mauna Loa, HI station (NOAA/ESRL 2021a). The concentration in 2019 at Mauna Loa was 411 ppm. The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 409 ppm in 2019.

[b] The values presented are global 2019 annual average mole fractions (NOAA/ESRL 2021b).

[c] The values presented are global 2019 annual average mole fractions (NOAA/ESRL 2021c).

[d] The values presented are global 2019 annual average mole fractions (NOAA/ESRL 2021d).

[e] The 2011 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2013).

[f] The rate of concentration change for CO_2 and CH_4 is the average rate of change between 2007 and 2019 (NOAA/ESRL 2021a). The rate of concentration change for N_2O, SF_6, and CF_4 is the average rate of change between 2005 and 2011 (IPCC 2013).

[g] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 7 ppb/year.

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

Source: Pre-industrial atmospheric concentrations, atmospheric lifetime, and rate of concentration changes for CH_4, N_2O, SF_6, and CF_4 are from IPCC (2013). The rate of concentration change for CO_2 is an average of the rates from 2007 through 2019 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2021a).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of GWPs, which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2013). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given increase in other greenhouse gases, the total warming is

greater than would happen in the absence of water vapor. Aircraft emissions of water vapor can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2013).

Carbon Dioxide (CO₂). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 411 ppmv in 2019, a 47 percent increase (IPCC 2013; NOAA/ESRL 2021a).[13],[14] The IPCC definitively states that "the increase of CO_2 … is caused by anthropogenic emissions from the use of fossil fuel as a source of energy and from land use and land use changes, in particular agriculture" (IPCC 2013). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Fifth Assessment Report*, the IPCC stated "it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together," of which CO_2 is the most important (IPCC 2013).

Methane (CH₄). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 167 percent since 1750, from a pre-industrial value of about 700 ppb to 1,866 ppb in 2019[15] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to about 7 ppb/year. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2007).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2013). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change.

Nitrous Oxide (N₂O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 23 percent since 1750, from a pre-industrial value of about 270 ppb to 331 ppb in 2019,[16] a concentration that has not been exceeded during the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2013).

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[13] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2013).

[14] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2013).

[15] This value is the global 2019 annual average mole fraction (NOAA/ESRL 2021b).

[16] This value is the global 2019 annual average (NOAA/ESRL 2021c).

Ozone (O_3). Ozone is present in both the upper stratosphere,[17] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[18] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 2013). The depletion of stratospheric ozone and its radiative forcing remains relatively unchanged since 2000 and recovery is expected to start occurring in the middle of the twenty-first century (WMO/UNEP 2014; WMO 2015).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the fourth largest increase in direct radiative forcing since the pre-industrial era, behind CO_2, black carbon, and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds (including CH_4) mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2013).

Halocarbons, Sulfur Hexafluoride, and Nitrogen Trifluoride. Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5 countries, including the United States,[19] beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

Hydrofluorocarbons, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that without further controls their contribution to overall radiative forcing will increase (IPCC 2013). In 2020, the U.S. Congress passed legislation designed to phase down the production and consumption of HFCs in the U.S., which would lead to lower emissions over time.

Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate,

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[17] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[18] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

[19] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2013).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO$_x$). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of stratospheric ozone when emitted from very high-altitude aircraft.[20] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2013). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[21] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2013). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2013).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, "despite the large uncertainty ranges on aerosol forcing, there is high confidence that aerosols have offset a substantial portion of greenhouse gas forcing" (IPCC 2013).[22] Although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[23] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a

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[20] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

[21] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2013).

[22] The IPCC (2013) defines high confidence as an indication of strong scientific evidence and agreement in this statement.

[23] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 2013).

positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2013). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A global warming potential is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2014). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[24] The relationship between kilotons (kt) of a gas and MMT CO_2 Eq. can be expressed as follows:

$$MMT\ CO_2\ Eq. = (kt\ of\ gas) \times (GWP) \times \left(\frac{MMT}{1,000\ kt}\right)$$

where,

> MMT CO_2 Eq. = Million metric tons of CO_2 equivalent
>
> kt = kilotons (equivalent to a thousand metric tons)
>
> GWP = Global warming potential
>
> MMT = Million metric tons
>
> GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±35 percent. Parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon, although other time horizon values are available.

...the global warming potential values used by Parties included in Annex I to the Convention (Annex I Parties) to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases shall be those listed in the column entitled "Global warming potential for given time horizon" in table 2.14 of the errata to the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, based on the effects of greenhouse gases over a 100-year time horizon...[25]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

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[24] Carbon comprises 12/44ths of carbon dioxide by weight.

[25] Framework Convention on Climate Change; Available online at: <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>; 31 January 2014; Report of the Conference of the Parties at its nineteenth session; held in Warsaw from 11 to 23 November 2013; Addendum; Part two: Action taken by the Conference of the Parties at its nineteenth session; Decision 24/CP.19; Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention; p. 2. (UNFCCC 2014).

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12	25
N_2O	114	298
HFC-23	270	14,800
HFC-32	4.9	675
HFC-41[d]	3.7	92
HFC-125	29	3,500
HFC-134a	14	1,430
HFC-143a	52	4,470
HFC-152a	1.4	124
HFC-227ea	34.2	3,220
HFC-236fa	240	9,810
CF_4	50,000	7,390
C_2F_6	10,000	12,200
C_3F_8	2,600	8,830
c-C_4F_8	3,200	10,300
SF_6	3,200	22,800
NF_3	740	17,200
Other Fluorinated Gases		See Annex 6

[a] 100-year time horizon.
[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.
[d] See Table A-1 of 40 CFR Part 98
Source: IPCC 2013.

Box 1-2: The *IPCC Fifth Assessment Report* and Global Warming Potentials

In 2014, the IPCC published its *Fifth Assessment Report* (AR5), which updated its comprehensive scientific assessment of climate change. Within the AR5 report, the GWP values of gases were revised relative to previous IPCC reports, namely the *IPCC Second Assessment Report* (SAR) (IPCC 1996), the *IPCC Third Assessment Report* (TAR) (IPCC 2001), and the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007). Although the AR4 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR5, the IPCC applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function in presenting updated GWP values. Additionally, the atmospheric lifetimes of some gases have been recalculated, and updated background concentrations were used. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons, and the indirect effects of methane on ozone have been adjusted to match more recent science. Table 1-3 presents the new GWP values, relative to those presented in the AR4 and using the 100-year time horizon common to UNFCCC reporting.

For consistency with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 GWP values, as required by the 2013 revision to the UNFCCC reporting

guidelines for national inventories.[26] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use GWPs from other IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

Table 1-3: Comparison of 100-Year GWP values

Gas	100-Year GWP Values				Comparison to AR4		
	SAR	AR4	AR5[a]	AR5 with feedbacks[b]	SAR	AR5	AR5 with feedbacks[b]
CO_2	1	1	1	1	NC	NC	NC
CH_4[c]	21	25	28	34	(4)	3	9
N_2O	310	298	265	298	12	(33)	NC
HFC-23	11,700	14,800	12,400	13,856	(3,100)	(2,400)	(944)
HFC-32	650	675	677	817	(25)	2	142
HFC-41	NA	92	116	NA	NA	24	NA
HFC-125	2,800	3,500	3,170	3,691	(700)	(330)	191
HFC-134a	1,300	1,430	1,300	1,549	(130)	(130)	119
HFC-143a	3,800	4,470	4,800	5,508	(670)	330	1,038
HFC-152a	140	124	138	167	16	14	43
HFC-227ea	2,900	3,220	3,350	3,860	(320)	130	640
HFC-236fa	6,300	9,810	8,060	8,998	(3,510)	(1,750)	(812)
CF_4	6,500	7,390	6,630	7,349	(890)	(760)	(41)
C_2F_6	9,200	12,200	11,100	12,340	(3,000)	(1,100)	140
C_3F_8	7,000	8,830	8,900	9,878	(1,830)	70	(1,048)
c-C_4F_8	8,700	10,300	9,540	10,592	(1,600)	(760)	292
SF_6	23,900	22,800	23,500	26,087	1,100	700	3,287
NF_3	NA	17,200	16,100	17,885	NA	(1,100)	685

Source: IPCC 2013, IPCC 2007, IPCC 2001, IPCC 1996.
Note: Parentheses indicate negative values.
NA (Not Applicable)
NC (No Change)
[a] The GWPs presented here are the ones most consistent with the methodology used in the AR4 report.
[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.
[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.

1.2 National Inventory Arrangements

The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the U.S. Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

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[26] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format (CRF) tables. EPA's Office of Transportation and Air Quality (OTAQ) is also involved in calculating emissions for the Inventory. The U.S. Department of State serves as the overall focal point to the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission calculations, QA/QC processes, and improvement planning at the individual source and sink category level. EPA, the inventory coordinator, compiles the entire Inventory into the proper reporting format for submission to the UNFCCC, and is responsible for the synthesis of information and for the consistent application of cross-cutting IPCC good practice across the Inventory.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the Inventory calculations via formal (e.g., interagency agreements) and informal relationships, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Other U.S. agencies provide official data for use in the Inventory. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides data on military fuel consumption and use of bunker fuels. Other U.S. agencies providing activity data for use in EPA's emission calculations include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the Inventory to the UNFCCC each April.

Figure 1-1: National Inventory Arrangements and Process Diagram
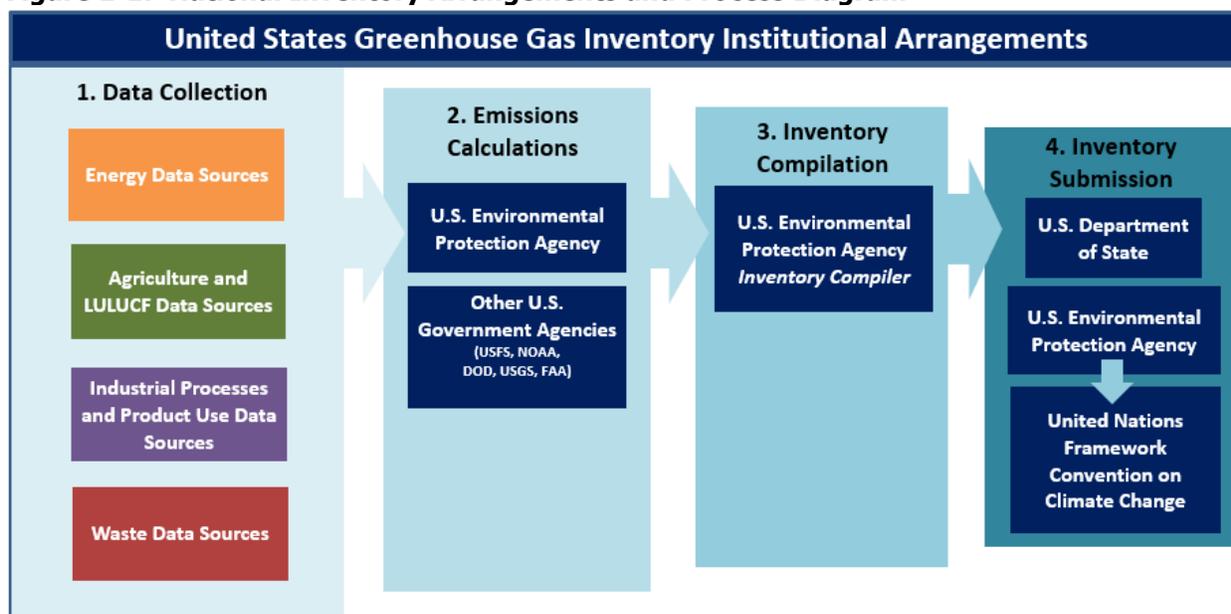
Overview of Inventory Data Sources by Source and Sink Category.

Energy	Agriculture and LULUCF	IPPU	Waste
Energy Information Administration	EPA Office of Land and Emergency Management	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	Alaska Department of Natural Resources	American Chemistry Council (ACC)	EPA Office of Land and Emergency Management

U.S. Department of Defense – Defense Logistics Agency	National Oceanic and Atmospheric Administration (NOAA)	U.S. Geological Survey (USGS) National Minerals Information Center	Data from research studies, trade publications, and industry associations
Federal Highway Administration	Association of American Plant Food Control Officials (AAPFCO)	American Iron and Steel Institute (AISI)	
EPA Acid Rain Program	U.S. Census Bureau	U.S. Aluminum Association	
EPA Office of Transportation and Air Quality MOVES Model	USDA Animal and Plant Health Inspection Service (APHIS)	U.S. International Trade Commission (USITC)	
EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Office of Air and Radiation	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Labor – Mine Safety and Health Administration	U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and Agricultural Research Service	Data from other U.S. government agencies, research studies, trade publications, and industry associations	
American Association of Railroads	USDA U.S. Forest Service Forest Inventory and Analysis Program		
American Public Transportation Association	USDA Natural Resource Conservation Service (NRCS)		
U.S. Department of Homeland Security	USDA Economic Research Service (ERS)		
U.S. Department of Energy and its National Laboratories	USDA Farm Service Agency (FSA)		
Federal Aviation Administration	U.S. Geological Survey (USGS)		
U.S. Department of Transportation & Bureau of Transportation Statistics	U.S. Department of the Interior (DOE), Bureau of Land Management (BLM)		
Data from research studies, trade publications, and industry associations	Data from research studies, trade publications, and industry associations		

Note: This table is not an exhaustive list of all data sources.

1.3 Inventory Process

This section describes EPA's approach to preparing the annual U.S. Inventory, which consists of a National Inventory Report (NIR) and Common Reporting Format (CRF) tables. The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for aggregating all emission estimates, conducting the overall uncertainty analysis of Inventory emissions and trends over time, and ensuring consistency and quality throughout the NIR and CRF tables. Emission calculations, including associated uncertainty analysis for individual sources and/or sink categories are the responsibility of individual source and sink category leads, who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC good practice guidance, the individual leads determine the most appropriate methodology and collect the best activity data to use in the emission and removal calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and contractors familiar with the sources. Each year, the coordinator overseas a multi-stage process for collecting information from each individual source and sink category lead to compile all information and data for the Inventory.

Methodology Development, Data Collection, and Emissions and Sink Estimation

Source and sink category leads at EPA collect input data and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Because EPA has been preparing the Inventory for many years, for most source and sink categories, the methodology for the previous year is applied to the new

"current" year of the Inventory, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category (e.g., the United States is implementing improvement efforts to apply a higher tiered approach for that category), then the source and/or sink category lead will develop and implement the new or refined methodology, gather the most appropriate activity data and emission factors (or in some cases direct emission measurements) for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Box ES-4 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The individual leads then update or create the relevant text and accompanying annexes for the Inventory. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRF, conducting quality assurance and quality control (QA/QC) checks, and category-level uncertainty analyses.

The treatment of confidential business information (CBI) in the Inventory is based on EPA internal guidelines, as well as regulations[27] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[28] In the Inventory, EPA is publishing only data values that meet the GHGRP aggregation criteria.[29] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Summary Data Compilation and Storage

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and annexes, and also aggregates the emission estimates into a summary data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the Inventory document. In addition to the data from each source and sink category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends sections of the Inventory report. Similarly, uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall Inventory uncertainty analysis (see Chapter 1.7). Electronic copies of each year's summary data files, which contain all the emission and sink estimates for the United States, are kept on a central server at EPA under the jurisdiction of the inventory coordinator.

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[27] 40 CFR part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See <https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6>.

[28] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at <https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf>.

[29] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, and in accordance with the reporting requirements of the UNFCCC. Also at this time, the Introduction, Executive Summary, and Trends in Greenhouse Gas Emissions chapters are drafted, to reflect the trends for the most recent year of the current Inventory. The analysis of trends necessitates gathering supplemental data, including weather and temperature conditions, economic activity and gross domestic product, population, atmospheric conditions, and the annual consumption of electricity, energy, and fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the Inventory document as separate analyses or side discussions in boxes within the text. Text boxes are also created to examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to match the specification of the UNFCCC reporting guidelines for National Inventory Reports.

Common Reporting Format Table Compilation

The CRF tables are compiled from individual tables completed by each individual source or sink category lead, which contain emissions and/or removals and activity data. The inventory coordinator integrates the category data into the UNFCCC's "CRF Reporter" for the United States, assuring consistency across all sectoral tables. The summary reports for emissions, methods, and emission factors used, the overview tables for completeness of estimates, the recalculation tables, the notation key completion tables, and the emission trends tables are then completed by the inventory coordinator. Internal automated quality checks on the CRF Reporter, as well as reviews by the category leads, are completed for the entire time series of CRF tables before submission.

QA/QC and Uncertainty

QA/QC and uncertainty analyses are guided by the QA/QC and Inventory coordinators, who help maintain the QA/QC plan and the overall uncertainty analysis procedures (see sections on QA/QC and Uncertainty, below). This coordinator works closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan and uncertainty analysis is implemented across all inventory sources. The inventory QA/QC plan, outlined in Section 1.7 and Annex 8, is consistent with the quality assurance procedures outlined by EPA and IPCC good practices. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC Reviews

The compilation of the inventory includes a two-stage review process, in addition to international technical expert review following submission of the report. During the first stage (the 30-day Expert Review period), a first draft of sectoral chapters of the document are sent to a select list of technical experts outside of EPA who are not directly involved in preparing estimates. The purpose of the Expert Review is to provide an objective review, encourage feedback on the methodological and data sources used in the current Inventory, especially for sources which have experienced any changes since the previous Inventory.

Once comments are received and addressed, the second stage, or second draft of the document is released for public review by publishing a notice in the U.S. Federal Register and posting the entire draft Inventory document on the EPA website. The Public Review period allows for a 30-day comment period and is open to the entire U.S. public. Comments may require further discussion with experts and/or additional research, and specific Inventory

improvements requiring further analysis as a result of comments are noted in the relevant category's Planned Improvement section. EPA publishes responses to comments received during both reviews with the publication of the final report on its website.

Following completion and submission of the report to the UNFCCC, the report also undergoes review by an independent international team of experts for adherence to UNFCCC reporting guidelines and IPCC guidance.[30] Feedback from all review processes that contribute to improving inventory quality over time are described further in Annex 8.

Final Submittal to UNFCCC and Document Publication

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final NIR and the accompanying CRF tables for electronic reporting. EPA, as the National Inventory focal point, sends the official submission of the U.S. Inventory to the UNFCCC using the CRF Reporter software, coordinating with the U.S. Department of State, the overall UNFCCC focal point. Concurrently, for timely public access, the report is also published on EPA's website.[31]

1.4 Methodology and Data Sources

Emissions of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). To a great extent, this report makes use of published official economic and physical statistics for activity data and emission factors. Depending on the emission source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses the IPCC methodologies when applicable, and supplements them with other available country-specific methodologies and data where possible. For examples, as noted earlier in this chapter, this report does use supplements and refinements to 2006 IPCC Guidelines in estimating emissions from wastewater, Low Voltage Anode Effects (LVAE) during aluminum production, drained organic soils, and management of wetlands. Choices made regarding the methodologies and data sources used are provided in conjunction with the discussion of each source category in the main body of the report. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Coastal Wetlands).

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[30] See <https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process>.

[31] See <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[32] A key category analysis identifies source or sink categories for focusing efforts to improve overall Inventory quality.

The *2006 IPCC Guidelines* (IPCC 2006) defines several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States. The first method, Approach 1, was implemented to identify the key categories without considering uncertainty in its calculations. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude. This analysis was performed twice; one analysis included sources and sinks from the Land Use, Land-Use Change, and Forestry (LULUCF) sector, the other analysis did not include the LULUCF categories. The second method, Approach 2, was then implemented to identify any additional key categories not already identified in Approach 1 level assessment. This analysis differs from Approach 1 by incorporating each category's uncertainty assessments (or proxies) in its calculations and was also performed twice to include or exclude LULUCF categories. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, a trend analysis can identify categories that significantly influence trends since 1990 by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change to trend) when sorted in descending order of absolute magnitude.

In addition to conducting Approach 1 and 2 level and trend assessments as described above, a qualitative assessment of the source categories was conducted to capture any additional key categories that were not identified using the previously described quantitative approaches. For this inventory, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information regarding the overall key category analysis in Annex 1 to this report.

Table 1-4: Key Categories for the United States (1990 and 2019)

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2019 Emissions (MMT CO$_2$ Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
1.A.3.b CO$_2$ Emissions from Mobile Combustion: Road	CO$_2$	•	•	•	•	•	•	•	•	1,510.5
1.A.1 CO$_2$ Emissions from Stationary Combustion - Coal - Electricity Generation	CO$_2$	•	•	•	•	•	•	•	•	973.5

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[32] See Chapter 4 Volume 1, "Methodological Choice and Identification of Key Categories" in IPCC (2006). See <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>.

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2019 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.1 CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	616.0
1.A.2 CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•	503.3
1.A.4.b CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•	•	•		275.3
1.A.2 CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•	269.7
1.A.4.a CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•	•	192.8
1.A.3.a CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•		•		178.5
1.A.5 CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•	•	•	•	•	•	128.8
1.A.4.b CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•			61.5
1.A.4.a CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•					55.3
1.A.3.e CO_2 Emissions from Mobile Combustion: Other	CO_2	•	•	•	•					53.7
1.A.2 CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•	49.5
1.B.2.a CO_2 Emissions from Petroleum Systems	CO_2	•	•	•	•	•	•	•	•	47.3

| CRF Source/Sink Categories | Gas | Approach 1 | | | | Approach 2 (includes uncertainty) | | | | 2019 Emissions (MMT CO$_2$ Eq.) |
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.B.2.b CO$_2$ Emissions from Natural Gas Systems	CO$_2$	•		•						37.2
1.A.3.c CO$_2$ Emissions from Mobile Combustion: Railways	CO$_2$	•		•						37.1
1.A.3.d CO$_2$ Emissions from Mobile Combustion: Marine	CO$_2$	•		•						32.1
1.A.5 CO$_2$ Emissions from Stationary Combustion - Oil - U.S. Territories	CO$_2$	•		•						19.5
1.A.1 CO$_2$ Emissions from Stationary Combustion - Oil - Electricity Generation	CO$_2$	•	•	•	•	•	•		•	16.2
1.A.5.b CO$_2$ Emissions from Mobile Combustion: Military	CO$_2$				•					5.3
1.A.5 CO$_2$ Emissions from Stationary Combustion - Gas - U.S. Territories	CO$_2$						•			2.5
1.A.4.a CO$_2$ Emissions from Stationary Combustion - Coal - Commercial	CO$_2$		•		•					1.6
1.A.4.b CO$_2$ Emissions from Stationary Combustion - Coal - Residential	CO$_2$						•		•	NO
1.B.2.b CH$_4$ Emissions from Natural Gas Systems	CH$_4$	•	•	•	•	•	•	•	•	157.6
1.B.1 Fugitive Emissions from Coal Mining	CH$_4$	•	•	•	•	•	•	•	•	47.4
1.B.2.a CH$_4$ Emissions from Petroleum Systems	CH$_4$	•	•	•	•	•	•	•	•	39.1
1.B.2 CH$_4$ Emissions from Abandoned Oil and Gas Wells	CH$_4$					•		•		6.6

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2019 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
1.A.4.b CH_4 Emissions from Stationary Combustion - Residential	CH_4					•		•		4.6
1.A.3.b CH_4 Emissions from Mobile Combustion: Road	CH_4						•			0.9
1.A.1 N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O					•		•		16.7
1.A.3.b N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•	•	•		•	9.3
Industrial Processes and Product Use										
2.C.1 CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•	41.3
2.A.1 CO_2 Emissions from Cement Production	CO_2	•		•						40.9
2.B.8 CO_2 Emissions from Petrochemical Production	CO_2	•	•	•	•					30.8
2.B.3 N_2O Emissions from Adipic Acid Production	N_2O		•		•					5.3
2.F.1 Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air Conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	133.4
2.F.4 Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs		•		•	•	•		•	16.3
2.F.2 Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					16.1

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2019 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
2.F.3 Emissions from Substitutes for Ozone Depleting Substances: Fire Protection	HFCs, PFCs						•			2.8
2.F.5 Emissions from Substitutes for Ozone Depleting Substances: Solvents	HFCs, PFCs						•			2.0
2.G SF_6 Emissions from Electrical Transmission and Distribution	SF_6	•	•	•	•		•		•	4.2
2.B.9 HFC-23 Emissions from HCFC-22 Production	HFCs	•	•	•	•		•		•	3.7
2.C.3 PFC Emissions from Aluminum Production	PFCs	•	•	•	•					1.8
Agriculture										
3.G CO_2 Emissions from Liming	CO_2						•			2.4
3.A.1 CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	•	•	•	•	•		•		172.3
3.B.1 CH_4 Emissions from Manure Management: Cattle	CH_4	•	•	•	•		•		•	35.4
3.B.4 CH_4 Emissions from Manure Management: Other Livestock	CH_4	•		•						26.9
3.C CH_4 Emissions from Rice Cultivation	CH_4					•		•		15.1
3.D.1 Direct N_2O Emissions from Agricultural Soil Management	N_2O	•	•	•	•	•	•	•	•	290.4
3.D.2 Indirect N_2O Emissions from Applied Nitrogen	N_2O	•	•	•	•	•	•	•	•	54.2
Waste										
5.A CH_4 Emissions from Landfills	CH_4	•	•	•	•	•	•	•	•	114.5
5.D CH_4 Emissions from Wastewater Treatment	CH_4	•		•		•				18.4

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2019 Emissions (MMT CO$_2$ Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
5.D N$_2$O Emissions from Wastewater Treatment	N$_2$O	•		•		•	•	•	•	26.4
Land Use, Land-Use Change, and Forestry										
4.E.2 Net CO$_2$ Emissions from Land Converted to Settlements	CO$_2$			•	•			•	•	79.2
4.B.2 Net CO$_2$ Emissions from Land Converted to Cropland	CO$_2$			•				•		54.2
4.C.1 Net CO$_2$ Emissions from Grassland Remaining Grassland	CO$_2$							•	•	14.5
4.B.1 Net CO$_2$ Emissions from Cropland Remaining Cropland	CO$_2$			•	•			•	•	(14.5)
4.C.2 Net CO$_2$ Emissions from Land Converted to Grassland	CO$_2$			•	•			•	•	(23.2)
4.A.2 Net CO$_2$ Emissions from Land Converted to Forest Land	CO$_2$			•				•		(99.1)
4.E.1 Net CO$_2$ Emissions from Settlements Remaining Settlements	CO$_2$			•	•			•	•	(124.1)
4.A.1 Net CO$_2$ Emissions from Forest Land Remaining Forest Land	CO$_2$			•	•			•	•	(691.8)
4.A.1 CH$_4$ Emissions from Forest Fires	CH$_4$				•					9.5
Subtotal Without LULUCF										**6,398.6**
Total Emissions Without LULUCF										**6,558.3**
Percent of Total Without LULUCF										**98%**
Subtotal With LULUCF										**5,598.0**
Total Emissions With LULUCF										**5,769.1**
Percent of Total With LULUCF										**97%**

NO (Not Occurring)

1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document, and improve the quality of its inventory over time. QA/QC activities on the Inventory are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory
- *Quality Assurance (QA):* expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice and the *2006 IPCC Guidelines* (IPCC 2006)
- *Quality Control (QC)*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts.
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years, especially for category-specific QC, prioritizing key categories
- *Interaction and Coordination:* promoting communication within the EPA, across Federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the Inventory. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

Figure 1-2: U.S. QA/QC Plan Summary

	Data Gathering	Data Documentation	Calculating Emissions	Cross-Cutting Coordination

Inventory Analyst	• Obtain data in electronic format (if possible)
	• Review spreadsheet construction
	  ○ Avoid hardwiring
	  ○ Use data validation
	  ○ Protect cells
	• Develop automatic checkers for:
	  ○ Outliers, negative values, or missing data
	  ○ Variable types match values
	  ○ Time series consistency
	• Maintain tracking tab for status of gathering efforts
		• Contact reports for non-electronic communications
		• Provide cell references for primary data elements
		• Obtain copies of all data sources
		• List and location of any working/external spreadsheets
		• Document assumptions
		• Complete QA/QC checklists
		• CRF and summary tab links
			• Clearly label parameters, units, and conversion factors
			• Review spreadsheet integrity
			  ○ Equations
			  ○ Units
			  ○ Inputs and outputs
			• Develop automated checkers for:
			  ○ Input ranges
			  ○ Calculations
			  ○ Emission aggregation
			  ○ Trend and IEF checks
				• Common starting versions for each inventory year
				• Utilize unalterable summary and CRF tab for each source spreadsheet for linking to a master summary spreadsheet
				• Follow strict version control procedures
				• Document QA/QC procedures

QA/QC Analyst	• Check input data for transcription errors • Inspect automatic checkers • Identify spreadsheet modifications that could provide additional QA/QC checks	• Check citations in spreadsheet and text for accuracy and style • Check reference docket for new citations • Review documentation for any data / methodology changes • Complete QA/QC checklists • CRF and summary tab links	• Reproduce calculations • Review time series consistency • Review changes in data/consistency with IPCC methodology	

Box 1-3: Use of IPCC Reference Approach to support Verification of Emissions from Fossil Fuel Combustion

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology for purposes of verification. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

In addition, based on the national QA/QC plan for the Inventory, some sector, subsector and category-specific QA/QC and verification checks have been developed. These checks follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific documentation and data files associated with individual sources. For each greenhouse gas emissions source or sink included in this Inventory, a minimum of general or Tier 1 QC analysis has been undertaken. Where QC activities for a particular category go beyond the minimum Tier 1 level, and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source or sink category sections in each sectoral chapter and Annex 8.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the Inventory. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the Expert Review and the Public Review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory data and methods.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

1.7 Uncertainty Analysis of Emission Estimates

Emissions calculated for the U.S. Inventory reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty estimates are an essential element of a complete and transparent emissions inventory that help inform and prioritize Inventory improvements. For the U.S. Inventory, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall Inventory, its trends, and each source and sink category.

The overall uncertainty estimate for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology, which employs a Monte Carlo Stochastic Simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall Inventory and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall Inventory uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve Inventory estimates. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce Inventory uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve emission estimation methods, and collect more detailed, measured, and representative data. Individual source chapters and Annex 7 both describe current ongoing and planned Inventory and uncertainty analysis improvements. Consistent with IPCC (2006), the United States has ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions in 1990 (base year) and 2019 are shown below in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the Total Net Emissions is estimated to be -6 to +6 percent in 1990 and -5 to +5 percent in 2019. When the *LULUCF* sector is excluded from the analysis the uncertainty is estimated to be -2 to +5 percent in 1990 and -2 to +4 percent in 2019.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)		Mean[b] (MMT CO_2 Eq.)	Standard Deviation[b] (MMT CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,113.5	5,008.6	5,349.7	-2%	5%	5,177.3	88.5
CH_4[d]	776.9	710.7	863.0	-9%	11%	785.8	38.7
N_2O[d]	452.7	368.3	581.4	-19%	28%	461.0	54.8
PFC, HFC, SF_6, and NF_3[d]	99.7	90.2	112.2	-9%	13%	100.3	5.6
Total	**6,442.7**	**6,311.7**	**6,748.8**	**-2%**	**5%**	**6,524.4**	**111.0**
LULUCF Emissions[e]	7.9	6.0	10.0	-24%	26%	8.0	1.0
LULUCF Carbon Stock Change Flux[f]	(908.7)	(1,221.6)	(741.6)	34%	-18%	(982.4)	122.3
LULUCF Sector Net Total[g]	**(900.8)**	**(1,213.8)**	**(733.6)**	**35%**	**-19%**	**(974.4)**	**122.3**
Net Emissions (Sources and Sinks)	**5,541.9**	**5,232.4**	**5,877.3**	**-6%**	**6%**	**5,550.0**	**164.7**

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Does not exceed 0.5 percent.

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5[th] percentile and the upper bound corresponding to 97.5[th] percentile.

b Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

c The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

d The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 1990.

e LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

f LULUCF Carbon Stock Change is the net C stock change from the following categories: Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements, and Land Converted to Settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

g The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2019 (MMT CO$_2$ Eq. and Percent)

Gas	2019 Emission Estimate (MMT CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO$_2$ Eq.)		(%)		Mean[b]	Standard Deviation[b] (MMT CO$_2$ Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO$_2$	5,255.8	5,129.9	5,461.8	-2%	4%	5,295.1	85.4
CH$_4$[d]	659.7	608.3	732.5	-8%	11%	670.1	31.6
N$_2$O[d]	457.1	367.5	598.2	-20%	31%	468.7	59.1
PFC, HFC, SF$_6$, and NF$_3$[d]	185.6	179.4	208.1	-3%	12%	193.1	7.4
Total	**6,558.3**	**6,417.7**	**6,845.6**	**-2%**	**4%**	**6,627.0**	**108.9**
LULUCF Emissions[e]	23.5	20.1	27.9	-14%	19%	23.9	2.0
LULUCF Carbon Stock Change Flux[f]	(812.7)	(1,089.1)	(664.0)	34%	-18%	(878.2)	108.4
LULUCF Sector Net Total[g]	**(789.2)**	**(1,064.9)**	**(640.0)**	**35%**	**-19%**	**(854.3)**	**108.4**
Net Emissions (Sources and Sinks)	**5,769.0**	**5,471.4**	**6,074.3**	**-5%**	**5%**	**5,772.8**	**153.7**

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Does not exceed 0.5 percent.

a The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5[th] percentile and the upper bound corresponding to 97.5[th] percentile.

b Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

c The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

d The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2019.

e LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

f LULUCF Carbon Stock Change is the net C stock change from the following categories: Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements, and Land Converted to Settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

g The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

In addition to the estimates of uncertainty associated with the current and base year emission estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2019) Inventory estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this Inventory as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty associated with this emission trend is referred to as trend uncertainty and is reported as between -3 and 13 percent between Inventory estimates between 1990 and 2019. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO$_2$ Eq. and Percent)

Gas/Source	Base Year Emissions[a]	2019 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO$_2$ Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO$_2$	5,113.5	5,255.8	3%	-2%	7%
CH$_4$	776.9	659.7	-15%	-26%	-3%
N$_2$O	452.7	457.1	1%	-27%	43%
HFCs, PFCs, SF$_6$, and NF$_3$	99.7	185.6	41%	68%	119%
Total Emissions[c]	**6,442,7**	**6,558.3**	**1%**	**-3%**	**7%**
LULUCF Emissions[d]	7.9	23.5	196%	124%	306%
LULUCF Carbon Stock Change Flux[e]	(908.7)	-812.7	-11%	-37%	27%
LULUCF Sector Net Total[f]	**(900.8)**	**(789.2)**	**-12%**	**-38%**	**25%**
Net Emissions (Sources and Sinks)[c]	**5,541.9**	**5,769.0**	**4%**	**-3%**	**13%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.
+ Does not exceed 0.05 MMT CO$_2$ Eq. or 0.5 percent.
[a] Base Year is 1990 for all sources.
[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5[th] percentile value and the upper bound corresponding to 97.5[th] percentile value.
[c] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in the energy sector totals.
[c] Totals exclude emissions for which uncertainty was not quantified.
[d] LULUCF emissions include the CH$_4$ and N$_2$O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH$_4$ emissions from *Land Converted to Coastal Wetlands*; and N$_2$O emissions from Forest Soils and Settlement Soils.
[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements*, and *Land Converted to Settlements*.

1.8 Completeness

This report, along with its accompanying CRF tables, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2019. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC and UNFCCC guidelines. In general, sources or sink categories not accounted for in this Inventory are excluded because they are not occurring in the United States, or because data are

unavailable to develop an estimate and/or the categories were determined to be insignificant[33] in terms of overall national emissions per UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks currently not included and seeking to find the data required to estimate related emissions and removals, focusing on categories that are anticipated to be significant. As such improvements are implemented, new emission and removal estimates are quantified and included in the Inventory, improving completeness of national estimates. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

1.9 Organization of Report

In accordance with the revision of the UNFCCC reporting guidelines agreed to at the nineteenth Conference of the Parties (UNFCCC 2014), this *Inventory of U.S. Greenhouse Gas Emissions and Sinks* is grouped into five sector-specific chapters consistent with the UN Common Reporting Framework, listed below in Table 1-8. In addition, chapters on Trends in Greenhouse Gas Emissions, Other information, and Recalculations and Improvements to be considered as part of the U.S. Inventory submission are included.

Table 1-8: IPCC Sector Descriptions

Chapter/IPCC Sector	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/IPCC Sector: Overview of emissions and trends for each IPCC defined sector.

CRF Source or Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with UNFCCC reporting guidelines.

Methodology: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors.

Uncertainty and Time Series Consistency: A discussion and quantification of the uncertainty in emission estimates and a discussion of time-series consistency.

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[33] See paragraph 32 of Decision 24/CP.19, the UNFCCC reporting guidelines on annual inventories for Parties included in Annex 1 to the Convention. Paragraph notes that "…An emission should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, and does not exceed 500 kt CO_2 Eq. The total national aggregate of estimated emissions for all gases and categories considered insignificant shall remain below 0.1 percent of the national total GHG emissions."

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1 Key Category Analysis

ANNEX 2 Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion

2.1.   Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion

2.2.   Methodology for Estimating the Carbon Content of Fossil Fuels

2.3.   Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels

ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

3.1.   Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion

3.2.   Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions

3.3.   Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption

3.4.   Methodology for Estimating CH_4 Emissions from Coal Mining

3.5.   Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems

3.6.   Methodology for Estimating CH_4 Emissions from Natural Gas Systems

3.7.   Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste

3.8.   Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

3.9.   Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

3.10.   Methodology for Estimating CH_4 Emissions from Enteric Fermentation

3.11.   Methodology for Estimating CH_4 and N_2O Emissions from Manure Management

3.12.   Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)

3.13.   Methodology for Estimating Net Carbon Stock Changes in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*

3.14.   Methodology for Estimating CH_4 Emissions from Landfills

ANNEX 4 IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion

ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included

ANNEX 6 Additional Information

6.1.   Global Warming Potential Values

6.2.   Ozone Depleting Substance Emissions

6.3.   Sulfur Dioxide Emissions

6.4.   Complete List of Source Categories

6.5.   Constants, Units, and Conversions

6.6.   Abbreviations

6.7.   Chemical Formulas

ANNEX 7 Uncertainty

7.1.   Overview

7.2.   Methodology and Results

7.3.   Reducing Uncertainty

7.4.   Planned Improvements

7.5.   Additional Information on Uncertainty Analyses by Source

ANNEX 8 QA/QC Procedures

8.1.   Background

8.2.   Purpose

2. Trends in Greenhouse Gas Emissions

2.1 Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2019, total gross U.S. greenhouse gas emissions were 6,558.3 million metric tons carbon dioxide equivalent (MMT CO_2 Eq.).[1] Total U.S. emissions have increased by 1.8 percent from 1990 to 2019, down from a high of 15.6 percent above 1990 levels in 2007. Emissions decreased from 2018 to 2019 by 1.7 percent (113.1 MMT CO_2 Eq.). Net emissions (i.e., including sinks) were 5,769.1 MMT CO_2 Eq. Overall, net emissions decreased 1.7 percent from 2018 to 2019 and decreased 13.0 percent from 2005 levels, as shown in Table 2-1. The decline reflects the combined impacts of many long-term trends, including population, economic growth, energy market trends, technological changes including energy efficiency, and carbon intensity of energy fuel choices. Between 2018 and 2019, the decrease in total greenhouse gas emissions was driven largely by a decrease in CO_2 emissions from fossil fuel combustion. The decrease in CO_2 emissions from fossil fuel combustion was a result of a 1 percent decrease in total energy use and reflects a continued shift from coal to less carbon intensive natural gas and renewables in the electric power sector.

Figure 2-1 through Figure 2-3 illustrate the overall trend in total U.S. emissions by gas, annual changes, and relative changes since 1990.

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[1] The gross emissions total presented in this report for the United States excludes emissions and sinks from removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and sinks from removals from LULUCF.

Figure 2-1: U.S. Greenhouse Gas Emissions by Gas
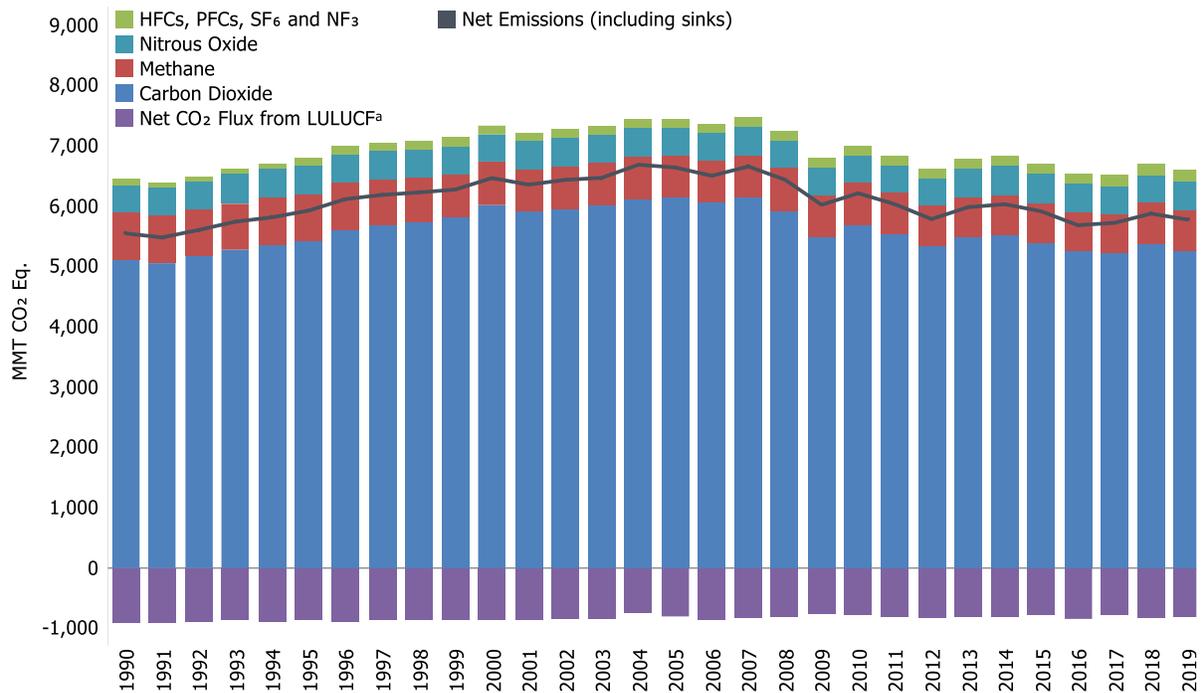
a The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Figure 2-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year
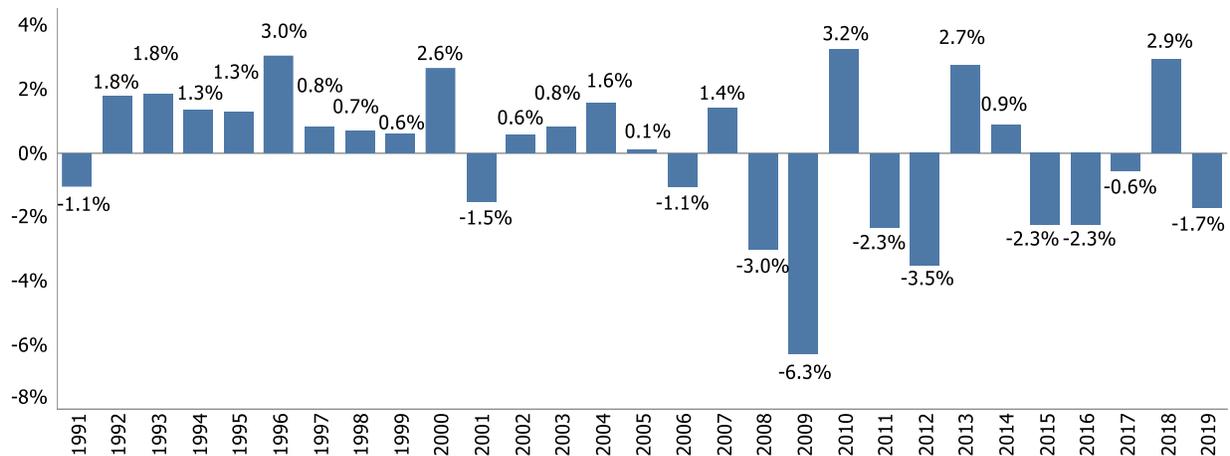
Figure 2-3: Change in Annual Gross U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0)
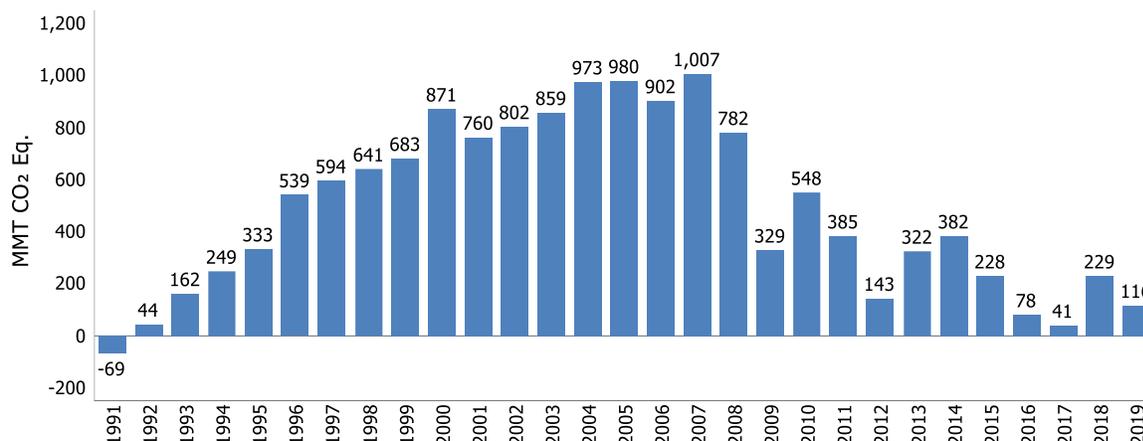
Overall, from 1990 to 2019, total emissions of CO_2 increased by 142.4 MMT CO_2 Eq. (2.8 percent), while total emissions of methane (CH_4) decreased by 117.2 MMT CO_2 Eq. (15.1 percent), and total emissions of nitrous oxide (N_2O) remained constant despite fluctuations throughout the time series. During the same period, aggregate weighted emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) rose by 86.0 MMT CO_2 Eq. (86.3 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 12.4 percent (812.7 MMT CO_2 Eq.) of total emissions in 2019.

Table 2-1 provides information on trends in emissions and sinks from all U.S. anthropogenic sources in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO_2	**5,113.5**	**6,134.5**	**5,371.8**	**5,248.0**	**5,207.8**	**5,375.5**	**5,255.8**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Transportation	*1,469.1*	*1,858.6*	*1,719.2*	*1,759.9*	*1,782.4*	*1,816.6*	*1,817.2*
Electric Power	*1,820.0*	*2,400.1*	*1,900.6*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.0*
Industrial	*853.8*	*852.9*	*797.3*	*792.5*	*790.1*	*813.6*	*822.5*
Residential	*338.6*	*358.9*	*317.3*	*292.8*	*293.4*	*338.1*	*336.8*
Commercial	*228.3*	*227.1*	*244.6*	*231.6*	*232.0*	*245.7*	*249.7*
U.S. Territories	*21.7*	*55.9*	*29.2*	*26.0*	*24.6*	*24.6*	*24.6*
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	9.7	12.1	32.4	21.8	25.0	37.1	47.3
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	47.9	43.6	40.6	42.6	41.3
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Natural Gas Systems	32.0	25.2	29.1	30.1	31.2	33.9	37.2
Petrochemical Production	21.6	27.4	28.1	28.3	28.9	29.3	30.8
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Incineration of Waste	8.1	12.7	11.5	11.5	11.5	11.5	11.5
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2

Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4
Aluminum Production	6.8	4.1	2.8	1.3	1.2	1.5	1.9
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219.4*	*230.7*	*317.7*	*316.6*	*312.3*	*319.6*	*316.2*
International Bunker Fuels[b]	*103.5*	*113.2*	*110.9*	*116.6*	*120.1*	*122.1*	*116.1*
CH_4[c]	**776.9**	**686.1**	**651.5**	**642.4**	**648.4**	**655.9**	**659.7**
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Natural Gas Systems	186.9	164.2	149.8	147.3	148.7	152.5	157.6
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Manure Management	37.1	51.6	57.9	59.6	59.9	61.7	62.4
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Petroleum Systems	48.9	39.5	41.5	39.2	39.3	37.3	39.1
Wastewater Treatment	20.2	20.1	18.8	18.7	18.5	18.4	18.4
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Stationary Combustion	8.6	7.8	8.5	7.9	7.6	8.5	8.7
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Mobile Combustion	6.4	4.0	2.6	2.5	2.5	2.4	2.4
Composting	0.4	1.9	2.1	2.3	2.4	2.3	2.3
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Petrochemical Production	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
Ferroalloy Production	+	+	+	+	+	+	+
Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**452.7**	**455.8**	**468.2**	**450.8**	**446.3**	**459.2**	**457.1**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Wastewater Treatment	18.7	23.0	25.4	25.9	26.4	26.1	26.4
Stationary Combustion	25.1	34.4	30.5	30.0	28.4	28.2	24.9
Manure Management	14.0	16.4	17.5	18.1	18.7	19.4	19.6
Mobile Combustion	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Composting	0.3	1.7	1.9	2.0	2.2	2.0	2.0

Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.2
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*
HFCs	**46.5**	**127.5**	**168.3**	**168.1**	**170.3**	**169.8**	**174.6**
Substitution of Ozone Depleting Substances[d]	0.2	107.3	163.6	164.9	164.7	166.0	170.5
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Electronics Industry	0.2	0.2	0.3	0.3	0.4	0.4	0.3
Magnesium Production and Processing	+	+	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.2**	**4.4**	**4.1**	**4.7**	**4.5**
Electronics Industry	2.8	3.3	3.1	2.9	2.9	3.0	2.7
Aluminum Production	21.5	3.4	2.1	1.4	1.1	1.6	1.8
Substitution of Ozone Depleting Substances[d]	+	+	+	+	+	0.1	0.1
SF$_6$	**28.8**	**11.8**	**5.5**	**6.0**	**5.9**	**5.7**	**5.9**
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
Magnesium Production and Processing	5.2	2.7	1.0	1.1	1.0	1.0	0.9
Electronics Industry	0.5	0.7	0.7	0.8	0.7	0.8	0.8
NF$_3$	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Unspecified Mix of HFCs, PFCs, SF$_6$, and NF$_3$	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+
Total Emissions (Sources)	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**
LULUCF Emissions (Sources)[c]	**7.9**	**16.8**	**27.8**	**13.2**	**26.0**	**23.4**	**23.5**
LULUCF CH$_4$ Emissions	5.0	9.3	16.6	7.7	15.3	13.8	13.8
LULUCF N$_2$O Emissions	3.0	7.5	11.3	5.5	10.6	9.7	9.7
LULUCF Carbon Stock Change[e]	**(908.7)**	**(804.8)**	**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
LULUCF Sector Net Total[f]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**
Net Emissions (Sources and Sinks)	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH$_4$ and N$_2$O are reported separately from gross emissions totals. LULUCF emissions include the CH$_4$ and N$_2$O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH$_4$ emissions from *Land Converted to Coastal Wetlands*; and N$_2$O emissions from Forest Soils and Settlement Soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Wetlands Remaining Wetlands*, *Land Converted to Wetlands*, *Settlements Remaining Settlements*, and *Land Converted to Settlements*. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO₂	**5,113,455**	**6,134,521**	**5,371,771**	**5,248,024**	**5,207,751**	**5,375,491**	**5,255,816**
Fossil Fuel Combustion	4,731,466	5,753,507	5,008,270	4,911,532	4,854,480	4,991,420	4,856,702
Transportation	*1,469,116*	*1,858,648*	*1,719,230*	*1,759,866*	*1,782,441*	*1,816,563*	*1,817,209*
Electric Power	*1,819,951*	*2,400,057*	*1,900,637*	*1,808,871*	*1,732,031*	*1,752,936*	*1,606,024*
Industrial	*853,808*	*852,895*	*797,270*	*792,496*	*790,069*	*813,569*	*822,470*
Residential	*338,578*	*358,898*	*317,304*	*292,764*	*293,397*	*338,058*	*336,752*
Commercial	*228,298*	*227,130*	*244,596*	*231,552*	*231,989*	*245,738*	*249,691*
U.S. Territories	*21,715*	*55,879*	*29,232*	*25,983*	*24,552*	*24,555*	*24,556*
Non-Energy Use of Fuels	112,766	129,135	108,476	99,840	113,539	129,728	128,763
Petroleum Systems	9,709	12,059	32,412	21,847	24,979	37,115	47,269
Iron and Steel Production & Metallurgical Coke Production	104,732	70,076	47,941	43,621	40,566	42,627	41,310
Cement Production	33,484	46,194	39,907	39,439	40,324	38,971	40,896
Natural Gas Systems	32,042	25,179	29,127	30,054	31,200	33,885	37,234
Petrochemical Production	21,611	27,383	28,062	28,310	28,910	29,314	30,792
Ammonia Production	13,047	9,177	10,616	10,245	11,112	12,163	12,272
Lime Production	11,700	14,552	13,342	12,630	12,882	13,106	12,112
Incineration of Waste	8,062	12,713	11,533	11,525	11,537	11,547	11,471
Other Process Uses of Carbonates	6,297	7,644	12,182	10,972	9,933	7,469	7,457
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,578	5,132	5,028	5,857	6,222
Urea Fertilization	2,417	3,504	4,728	4,877	5,051	5,192	5,341
Carbon Dioxide Consumption	1,472	1,375	4,940	4,640	4,580	4,130	4,870
Liming	4,667	4,349	3,737	3,081	3,080	2,248	2,442
Aluminum Production	6,831	4,142	2,767	1,334	1,205	1,451	1,880
Soda Ash Production	1,431	1,655	1,714	1,723	1,753	1,714	1,792
Ferroalloy Production	2,152	1,392	1,960	1,796	1,975	2,063	1,598
Titanium Dioxide Production	1,195	1,755	1,635	1,662	1,688	1,541	1,474
Glass Production	1,535	1,928	1,299	1,249	1,296	1,305	1,280
Zinc Production	632	1,030	886	838	900	999	1,026
Phosphoric Acid Production	1,529	1,342	999	998	1,028	940	891
Lead Production	516	553	473	500	513	513	540
Carbide Production and Consumption	370	213	176	170	181	184	175
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Magnesium Production and Processing	1	3	3	3	3	1	1
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219,413*	*230,700*	*317,742*	*316,610*	*312,304*	*319,647*	*316,191*
International Bunker Fuels[b]	*103,463*	*113,232*	*110,908*	*116,611*	*120,121*	*122,112*	*116,064*
CH₄[c]	**31,075**	**27,445**	**26,061**	**25,696**	**25,935**	**26,237**	**26,389**
Enteric Fermentation	6,588	6,772	6,675	6,890	7,032	7,119	7,142
Natural Gas Systems	7,478	6,567	5,994	5,894	5,949	6,101	6,305
Landfills	7,063	5,255	4,456	4,321	4,375	4,482	4,580
Manure Management	1,485	2,062	2,316	2,385	2,395	2,467	2,495
Coal Mining	3,860	2,565	2,449	2,154	2,191	2,109	1,895

Petroleum Systems	1,955	1,579	1,659	1,568	1,574	1,492	1,563
Wastewater Treatment	806	803	753	747	739	737	736
Rice Cultivation	640	720	648	631	596	623	602
Stationary Combustion	344	313	339	315	306	342	346
Abandoned Oil and Gas Wells	271	287	294	296	288	290	263
Abandoned Underground Coal Mines	288	264	256	268	257	247	237
Mobile Combustion	256	158	105	102	100	98	95
Composting	15	75	85	91	98	90	91
Field Burning of Agricultural Residues	15	17	18	17	17	17	17
Petrochemical Production	9	3	7	10	10	12	13
Anaerobic Digestion at Biogas Facilities	1	2	7	7	7	7	7
Ferroalloy Production	1	+	1	1	1	1	+
Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*4*	*4*	*4*
N$_2$O[c]	**1,519**	**1,530**	**1,571**	**1,513**	**1,498**	**1,541**	**1,534**
Agricultural Soil Management	1,060	1,052	1,169	1,108	1,099	1,135	1,156
Wastewater Treatment	63	77	85	87	89	88	88
Stationary Combustion	84	115	102	101	95	95	84
Manure Management	47	55	59	61	63	65	66
Mobile Combustion	150	139	73	70	67	63	60
Nitric Acid Production	41	38	39	34	31	32	34
Adipic Acid Production	51	24	14	23	25	35	18
N$_2$O from Product Uses	14	14	14	14	14	14	14
Composting	1	6	6	7	7	7	7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	6	6	5	5	5
Incineration of Waste	2	1	1	1	1	1	1
Electronics Industry	+	+	1	1	1	1	1
Field Burning of Agricultural Residues	1	1	1	1	1	1	1
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*4*	*4*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[d]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances[d]	+	+	+	+	+	+	+
SF$_6$	**1**	**1**	**+**	**+**	**+**	**+**	**+**

Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
NF₃	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
Unspecified Mix of HFCs, PFCs, SF₆, and NF₃	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.5 kt.

M - Mixture of multiple gases

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of LULUCF CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

Emissions of all gases can be summed from each source category into a set of five sectors defined by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-4 and Table 2-3 illustrate that over the thirty-year period of 1990 to 2019, total emissions from the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 66.7 MMT CO_2 Eq. (1.3 percent), 28.2 MMT CO_2 Eq. (8.1 percent), and 73.3 MMT CO_2 Eq. (13.2 percent), respectively. Emissions from the Waste sector decreased by 52.4 MMT CO_2 Eq. (24.2 percent). Over the same period, total C sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector decreased by 96.0 MMT CO_2 (10.6 percent decrease in total C sequestration), and emissions from the LULUCF sector increased by 15.5 MMT CO_2 Eq. (196.1 percent).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector
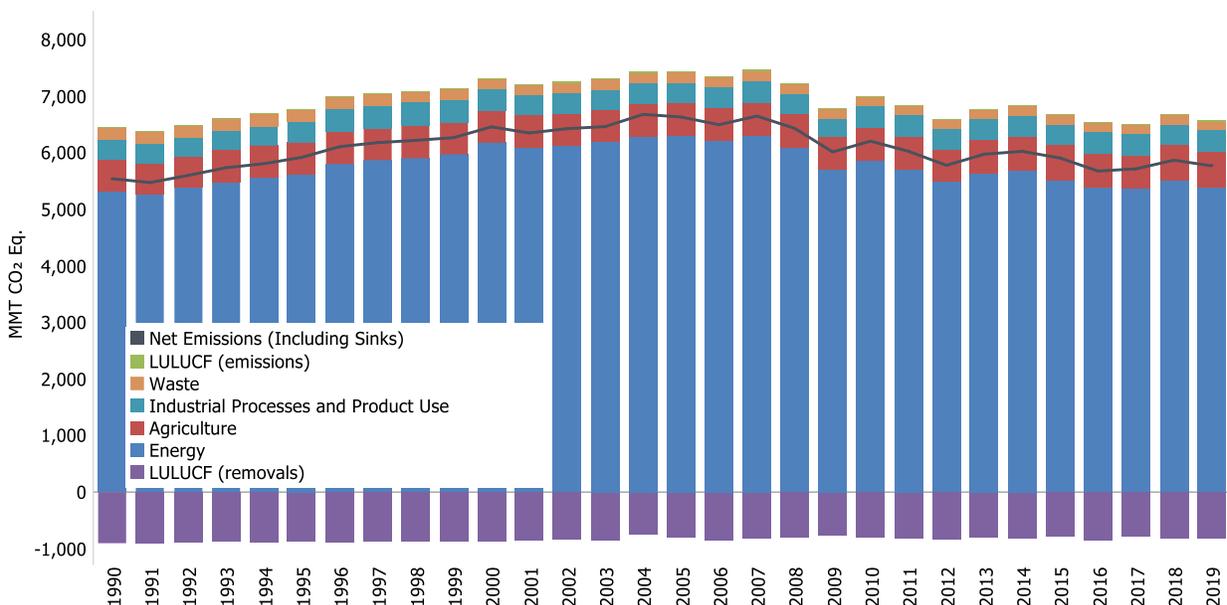
Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO$_2$ Eq.)

Chapter/IPCC Sector	1990	2005	2015	2016	2017	2018	2019
Energy	**5,325.6**	**6,302.3**	**5,519.8**	**5,390.9**	**5,351.0**	**5,518.1**	**5,392.3**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Natural Gas Systems	219.0	189.4	179.0	177.4	179.9	186.4	194.9
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	58.6	51.5	73.9	61.1	64.4	74.5	86.4
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Stationary Combustion	33.7	42.2	39.0	37.9	36.1	36.8	33.5
Mobile Combustion	51.1	45.5	24.4	23.4	22.3	21.3	20.3
Incineration of Waste	8.5	13.1	11.8	11.8	11.8	11.9	11.8
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Industrial Processes and Product Use	**345.6**	**365.7**	**375.4**	**368.0**	**367.7**	**371.3**	**373.7**
Substitution of Ozone Depleting Substances	0.2	107.3	163.6	164.9	164.7	166.1	170.6
Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	47.9	43.6	40.6	42.6	41.3
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Petrochemical Production	21.8	27.5	28.2	28.6	29.2	29.6	31.1
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Electronics Industry	3.6	4.8	5.0	5.0	4.9	5.1	4.6
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
N$_2$O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Aluminum Production	28.3	7.6	4.9	2.7	2.3	3.1	3.6
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Magnesium Production and Processing	5.2	2.7	1.1	1.2	1.1	1.1	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**555.3**	**577.1**	**616.1**	**604.4**	**605.5**	**621.0**	**628.6**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Manure Management	51.1	67.9	75.4	77.7	78.5	81.1	82.0
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4

Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Waste	**216.2**	**178.0**	**159.8**	**157.1**	**159.0**	**161.1**	**163.7**
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Wastewater Treatment	38.9	43.0	44.2	44.6	44.9	44.6	44.8
Composting	0.7	3.5	4.0	4.3	4.6	4.3	4.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
Total Emissions (Sources)[a]	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**
LULUCF Sector Net Total[b]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**
Forest land	(884.1)	(751.4)	(749.5)	(814.7)	(740.0)	(781.4)	(774.6)
Cropland	28.6	23.2	43.2	31.7	32.3	37.7	39.7
Grassland	2.2	(29.4)	(10.1)	(13.7)	(12.5)	(11.9)	(8.0)
Wetlands	(2.8)	(1.9)	(3.9)	(3.9)	(3.8)	(3.9)	(3.9)
Settlements	(44.7)	(28.5)	(43.5)	(42.2)	(42.1)	(42.0)	(42.4)
Net Emission (Sources and Sinks)[c]	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Total emissions without LULUCF.

[b] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[c] Net emissions with LULUCF.

Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2019. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-5 and Figure 2-6). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Energy chapter).

In 2019, approximately 80 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 20 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy use is presented here with more detail in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (40.6 percent and 9.5 percent of total U.S. emissions of each gas, respectively). Table 2-4 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-5: 2019 Energy Chapter Greenhouse Gas Sources

CO₂ Emissions from Fossil Fuel Combustion — 4,857

Energy as a Portion of All Emissions

Waste
Energy
IPPU
Agriculture

82.2%
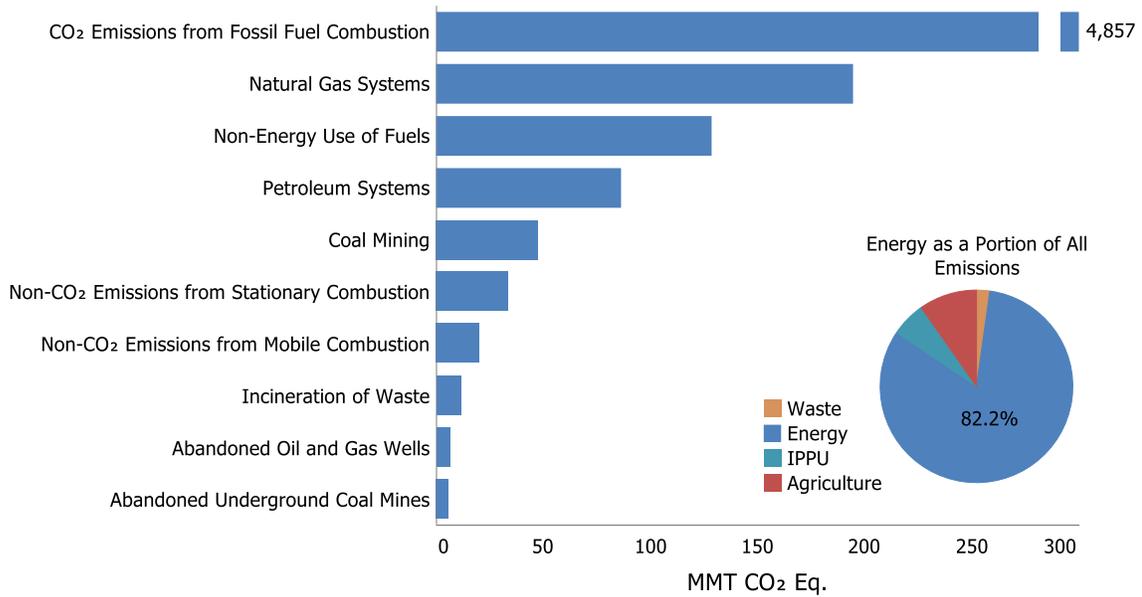
MMT CO₂ Eq.

Figure 2-6: Trends in Energy Chapter Greenhouse Gas Sources

MMT CO₂ Eq.

Incineration of Waste
U.S Territories Fossil Fuel Combustion
Non-Energy Use of Fuels
Commerical Fossil Fuel Combustion
Fugitive Emissions
Residential Fossil Fuel Combustion
Industrial Fossil Fuel Combustion
Transportation Fossil Fuel Combustion
Electric Power Fossil Fuel Combustion
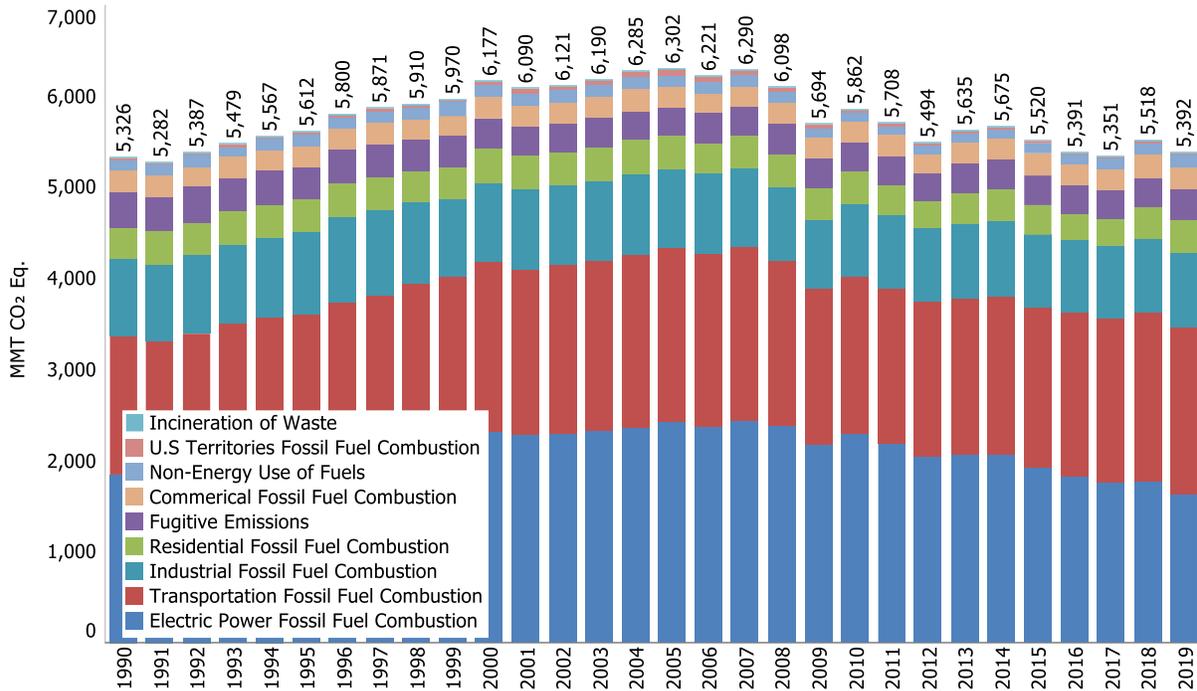
Table 2-4: Emissions from Energy (MMT CO$_2$ Eq.)[2]

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO$_2$	**4,894.1**	**5,932.6**	**5,189.8**	**5,074.8**	**5,035.7**	**5,203.7**	**5,081.4**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Transportation	*1,469.1*	*1,858.6*	*1,719.2*	*1,759.9*	*1,782.4*	*1,816.6*	*1,817.2*
Electric Power	*1,820.0*	*2,400.1*	*1,900.6*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.0*
Industrial	*853.8*	*852.9*	*797.3*	*792.5*	*790.1*	*813.6*	*822.5*
Residential	*338.6*	*358.9*	*317.3*	*292.8*	*293.4*	*338.1*	*336.8*
Commercial	*228.3*	*227.1*	*244.6*	*231.6*	*232.0*	*245.7*	*249.7*
U.S. Territories	*21.7*	*55.9*	*29.2*	*26.0*	*24.6*	*24.6*	*24.6*
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	9.7	12.1	32.4	21.8	25.0	37.1	47.3
Natural Gas Systems	32.0	25.2	29.1	30.1	31.2	33.9	37.2
Incineration of Waste	8.1	12.7	11.5	11.5	11.5	11.5	11.5
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*224.7*	*215.7*	*211.5*	*219.8*	*216.5*
International Bunker Fuels[b]	*103.5*	*113.2*	*110.9*	*116.6*	*120.1*	*122.1*	*116.1*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*78.9*	*81.2*	*82.1*	*81.9*	*82.6*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*14.1*	*19.6*	*18.7*	*17.9*	*17.1*
CH$_4$	**361.3**	**293.3**	**277.4**	**264.9**	**266.6**	**267.0**	**267.6**
Natural Gas Systems	186.9	164.2	149.8	147.3	148.7	152.5	157.6
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Petroleum Systems	48.9	39.5	41.5	39.2	39.3	37.3	39.1
Stationary Combustion	8.6	7.8	8.5	7.9	7.6	8.5	8.7
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Mobile Combustion	6.4	4.0	2.6	2.5	2.5	2.4	2.4
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N$_2$O	**70.3**	**76.3**	**52.6**	**51.2**	**48.6**	**47.4**	**43.2**
Stationary Combustion	25.1	34.4	30.5	30.0	28.4	28.2	24.9
Mobile Combustion	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*
Total	**5,325.6**	**6,302.3**	**5,519.8**	**5,390.9**	**5,351.0**	**5,518.1**	**5,392.3**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO$_2$ Eq.

[a] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

CO$_2$ Emissions from Fossil Fuel Combustion

As the largest contributor to U.S. greenhouse gas emissions, CO$_2$ from fossil fuel combustion has accounted for approximately 74 percent of gross emissions across the time series. Within the United States, fossil fuel combustion accounted for 92.4 percent of CO$_2$ emissions in 2019. Emissions from this source category grew by 2.6

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[2] The full time-series data is available in Common Reporting Format (CRF) Tables included in the U.S. UNFCCC submission and in CSV format available at <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

percent (125.2 MMT CO_2 Eq.) from 1990 to 2019 and were responsible for most of the increase in national emissions during this period. Conversely, CO_2 emissions from fossil fuel combustion decreased by 896.8 MMT CO_2 Eq. from 2005 and by 489.6 MMT CO_2 Eq. from 2010, representing decreases of approximately 15.6 percent between 2005 and 2019 and 9.2 percent between 2010 and 2019. From 2018 to 2019, these emissions decreased by 2.7 percent (134.7 MMT CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the main factor influencing U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion since 1990 are affected by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, carbon intensity of energy fuel choices, and seasonal temperatures. CO_2 emissions from coal combustion gradually increased between 1990 and 2007, then began to decrease at a faster rate from 2008 to 2019. CO_2 emissions from natural gas combustion remained relatively constant, with a slight increase between 1990 and 2009, then began to consistently increase between 2010 and 2019. The replacement of coal combustion with natural gas combustion was largely driven by new discoveries of natural gas fields and advancements in drilling technologies, which led to more competitive natural gas prices. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by a number of factors, including the relative price of coal and alternative sources, the ability to switch fuels, and longer-term trends in coal markets. Likewise, warmer winters lead to a decrease in heating degree days and result in a decreased demand for heating fuel and electricity for heat in the residential and commercial sectors, which leads to a decrease in emissions from reduced fuel consumption.

Fossil fuel combustion CO_2 emissions also depend on the type of fuel consumed or energy used and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower C content of natural gas (see Table A-28 in Annex 2.1 for more detail on the C Content Coefficient of different fossil fuels).

Recent trends in CO_2 emissions from fossil fuel combustion have been strongly influenced by trends in the electric power sector, which from 1990 to 2017 accounted for the largest share of emissions from this source (see Figure 2-18). Electric power sector emissions are driven by the total amount of electricity generated to meet electricity demand and the carbon intensity of the energy mix used to produce the electricity. From 1990 to 2005, power sector CO_2 emissions increased 32 percent with a 34 percent increase in generation (see Figure 2-9). From 2005 to 2019, power sector CO_2 emissions dropped 33 percent while generation remained relatively flat (a 2 percent increase). The types of fuel consumed to produce electricity have shifted over time, impacting emission trends. Electricity generation from lower carbon intensity renewable energy sources increased by 115 percent from 2005 to 2019 and natural gas generation increased by 116 percent while coal generation decreased by 52 percent over the same time period (see Table 3-12 for more detail on electricity generation by source). The decrease in coal-powered electricity generation and increase in natural gas and renewable energy electricity generation have contributed to the 33 percent decrease in overall CO_2 emissions from electric power generation from 2005 to 2019 (see Figure 2-9). Between 2018 and 2019, emissions from the electric power sector decreased 8.4 percent due to a decrease in electric power generation of 1.4 percent and a decrease in the carbon intensity of the electric power energy mix reflecting the continued shift in the share of electric power generation from coal to natural gas and renewable energy.

Petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which represents the largest source of CO_2 emissions from fossil fuel combustion in 2019. Emissions from petroleum consumption for transportation (including bunker fuels) have increased by 4.9 percent since 2015; this trend can be primarily attributed to a 5.4 percent increase in vehicle miles traveled (VMT) over the same time period. Fuel economy of light-duty vehicles is another important factor. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period and has slowed the rate of increase of CO_2 emissions.

Overall, across all sectors, there was a 2.7 percent decrease in total CO_2 emissions from fossil fuel combustion from 2018 to 2019 and a 3.0 percent reduction since 2015. Carbon dioxide emissions from fossil fuel combustion, separated by end-use sector, are presented in Table 2-5 and Figure 2-7 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Figure 2-8 further describes direct and indirect CO_2 emissions from fossil fuel combustion, separated by end-use sector. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total fuel consumption and appropriate fuel properties described below. (Any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.)

- *Transportation.* EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.

- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)

- *Electric Power.* EIA's fuel consumption data for the electric power sector are comprised of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public. (Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)

- *Residential.* EIA's fuel consumption data for the residential sector consist of living quarters for private households.

- *Commercial.* EIA's fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2015	2016	2017	2018	2019
Transportation	**1,472.2**	**1,863.4**	**1,723.5**	**1,764.1**	**1,786.8**	**1,821.2**	**1,821.9**
Combustion	1,469.1	1,858.6	1,719.2	1,759.9	1,782.4	1,816.6	1,817.2
Electricity	3.0	4.7	4.3	4.2	4.3	4.7	4.7
Industrial	**1,540.2**	**1,589.2**	**1,346.8**	**1,310.1**	**1,294.5**	**1,314.9**	**1,287.8**
Combustion	853.8	852.9	797.3	792.5	790.1	813.6	822.5
Electricity	686.4	736.3	549.5	517.6	504.4	501.3	465.3
Residential	**931.3**	**1,214.9**	**1,001.1**	**946.2**	**910.5**	**980.2**	**920.3**
Combustion	338.6	358.9	317.3	292.8	293.4	338.1	336.8
Electricity	592.7	856.0	683.8	653.5	617.1	642.1	583.5
Commercial	**766.0**	**1,030.1**	**907.6**	**865.2**	**838.2**	**850.6**	**802.1**
Combustion	228.3	227.1	244.6	231.6	232.0	245.7	249.7
Electricity	537.7	803.0	663.0	633.6	606.2	604.8	552.4
U.S. Territories[a]	**21.7**	**55.9**	**29.2**	**26.0**	**24.6**	**24.6**	**24.6**
Total	**4,731.5**	**5,753.5**	**5,008.3**	**4,911.5**	**4,854.5**	**4,991.4**	**4,856.7**
Electric Power	**1,820.0**	**2,400.1**	**1,900.6**	**1,808.9**	**1,732.0**	**1,752.9**	**1,606.0**

Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.
[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

Figure 2-7: 2019 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type
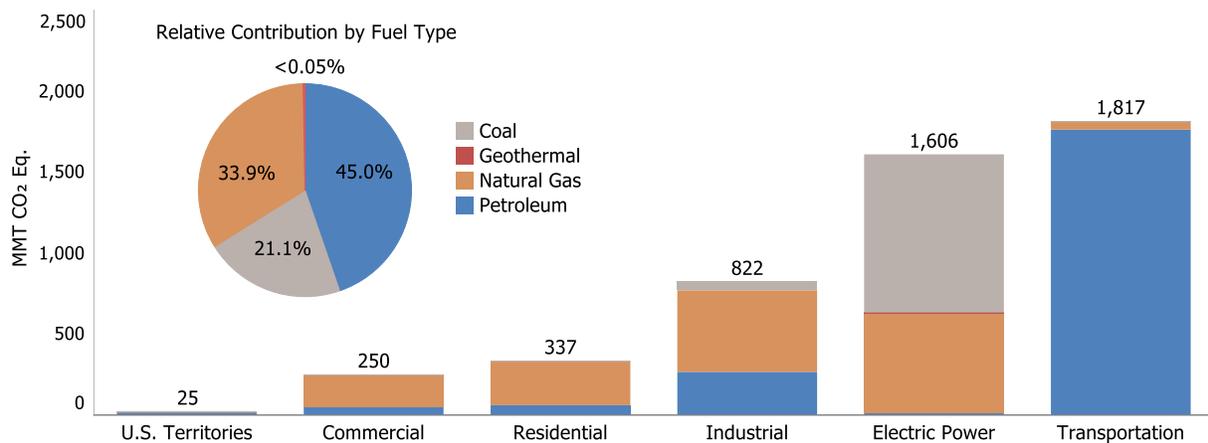
Note on Figure 2-7: Fossil Fuel Combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure 2-8: 2019 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion
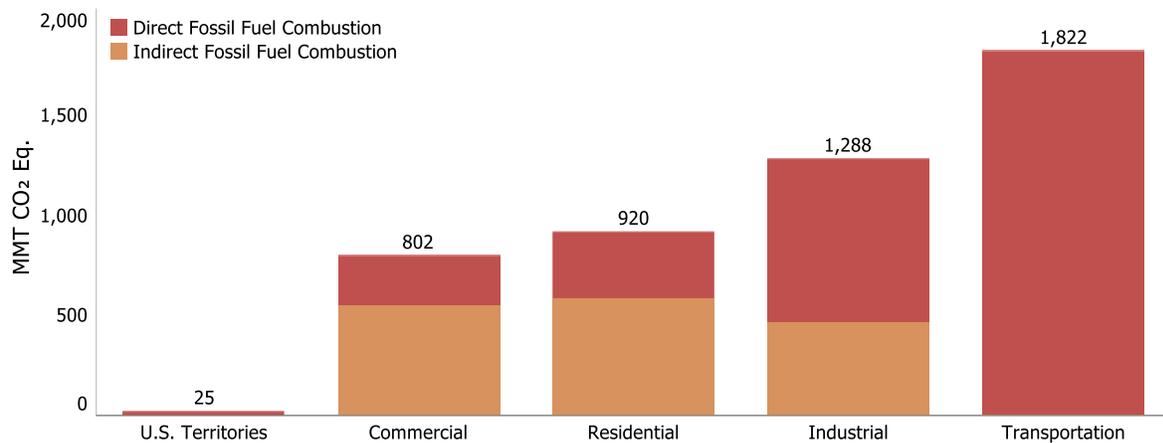
Electric power was the second largest emitter of CO_2 in 2019 (surpassed by transportation); electric power generators used 31 percent of U.S. energy from fossil fuels and emitted 33 percent of the CO_2 from fossil fuel combustion in 2019. Changes in electricity demand and the carbon intensity of fuels used for electric power generation have a significant impact on CO_2 emissions. Carbon dioxide emissions from the electric power sector have decreased by approximately 12 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has significantly decreased by 16 percent during that same timeframe. This decoupling of electric power generation and the resulting CO_2 emissions is shown below in Figure 2-9.

Figure 2-9: Electric Power Generation (Billion kWh) and Emissions
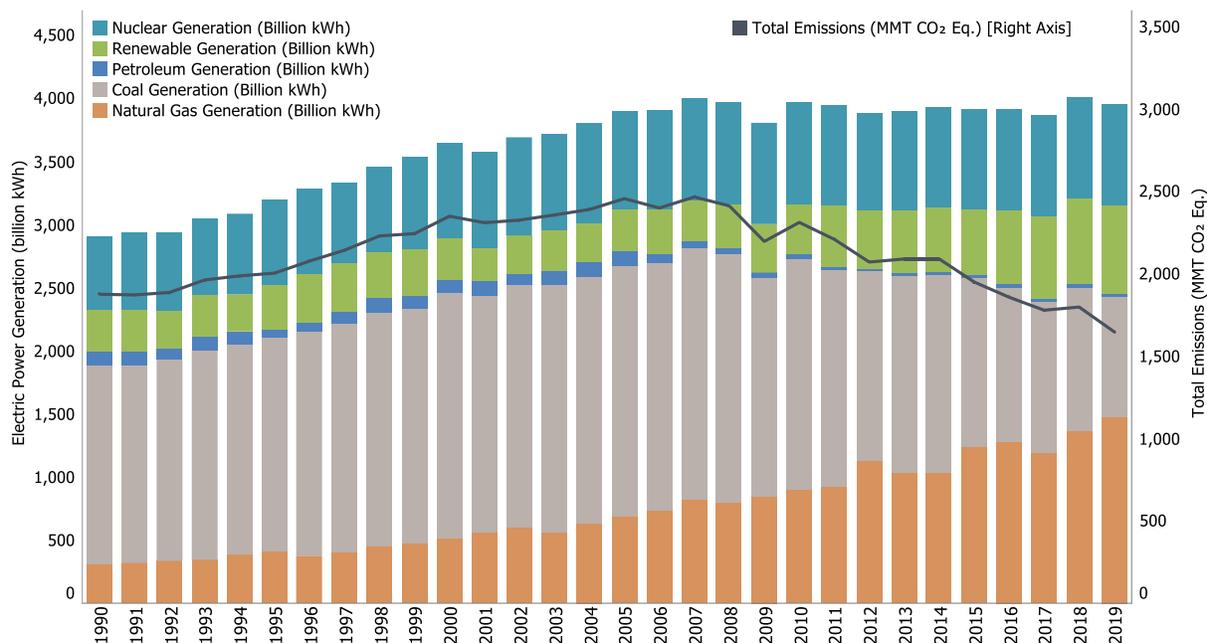
Electric power CO_2 emissions can also be allocated to the end-use sectors that use electricity, as presented in Table 2-5. With electricity CO_2 emissions allocated to end-use sectors, the transportation end-use sector represents the largest source of fossil fuel combustion emissions accounting for 1,821.9 MMT CO_2 Eq. in 2019 or approximately 38 percent of total CO_2 emissions from fossil fuel combustion. The industrial end-use sector accounted for 27 percent of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. The residential and commercial end-use sectors accounted for 19 and 17 percent, respectively, of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. Both of these end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 63 and 69 percent of emissions from the residential and commercial end-use sectors, respectively.

Other Significant Trends in Energy

Other significant trends in emissions from energy source categories (Figure 2-6) over the thirty-year period from 1990 through 2019 included the following:

- Methane emissions from natural gas systems and petroleum systems (combined here) decreased 39.1 MMT CO_2 Eq. (16.6 percent decrease from 1990 to 2019) or from 235.8 MMT CO_2 Eq. in 1990 to 196.7 MMT CO_2 Eq. in 2019. Natural gas systems CH_4 emissions decreased by 29.3 MMT CO_2 Eq. (15.7 percent) since 1990, largely due to a decrease in emissions from distribution, transmission and storage, processing, and exploration. The decrease in distribution is largely due to decreased emissions from pipelines and distribution station leaks, and the decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and leaks). At the same time, emissions from the natural gas production segment increased. Petroleum systems CH_4 emissions decreased by 9.8 MMT CO_2 Eq. (or 20.1 percent) since 1990. This decrease is due primarily to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Carbon dioxide emissions from natural gas and petroleum systems increased by 42.8 MMT CO_2 Eq. (102.4 percent) from 1990 to 2019. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.

- Methane emissions from coal mining decreased by 49.1 MMT CO_2 Eq. (50.9 percent) from 1990 through 2019, primarily due to a decrease in the number of active mines and annual coal production over the time period.

- Nitrous oxide emissions from mobile combustion decreased by 26.8 MMT CO_2 Eq. (58.9 percent) from 1990 through 2019, primarily as a result of national vehicle criteria pollutant emissions standards and emission control technologies for on-road vehicles.

- Carbon dioxide emissions from non-energy uses of fossil fuels increased by 16.0 MMT CO_2 Eq. (14.2 percent) from 1990 through 2019. Emissions from non-energy uses of fossil fuels were 128.8 MMT CO_2 Eq. in 2019, which constituted 2.4 percent of total national CO_2 emissions, approximately the same proportion as in 1990.

- Carbon dioxide emissions from incineration of waste (11.5 MMT CO_2 Eq. in 2019) increased by 3.4 MMT CO_2 Eq. (42.3 percent) from 1990 through 2019, as the volume of scrap tires and other fossil C-containing materials in waste increased.

Industrial Processes and Product Use

In many cases, greenhouse gas emissions are generated and emitted in two different ways. First, they are generated and emitted as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically or physically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process.

Second, industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are also emitted through use by a number of other industrial sources in the United States. These industries include the electronics industry, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by the electronics industry and anesthetic and aerosol applications. Figure 2-10 and Table 2-6 presents greenhouse gas emissions from industrial processes and product use by source category. Overall, emission sources in the Industrial Processes and Product Use (IPPU) chapter account for 5.7 percent of U.S. greenhouse gas emissions in 2019.

Figure 2-10: 2019 Industrial Processes and Product Use Chapter Greenhouse Gas Source

Substitution of Ozone Depleting Substances — 171

Iron and Steel Production & Metallurgical Coke Production

Cement Production

Petrochemical Production

Ammonia Production

Lime Production

Nitric Acid Production

Other Process Uses of Carbonates

Urea Consumption for Non-Agricultural Purposes

Adipic Acid Production

Carbon Dioxide Consumption

Electronics Industry

Electrical Transmission and Distribution

N₂O from Product Uses

HCFC-22 Production

Aluminum Production

Soda Ash Production

Ferroalloy Production

Titanium Dioxide Production

Caprolactam, Glyoxal, and Glyoxylic Acid Production

Glass Production

Zinc Production

Magnesium Production and Processing

Phosphoric Acid Production

Lead Production

Carbide Production and Consumption — < 0.5

MMT CO₂ Eq.

Industrial Processes and Product Use as a Portion of All Emissions

5.7%

Energy
Agriculture
IPPU
Waste

Figure 2-11: Trends in Industrial Processes and Product Use Chapter Greenhouse Gas Sources
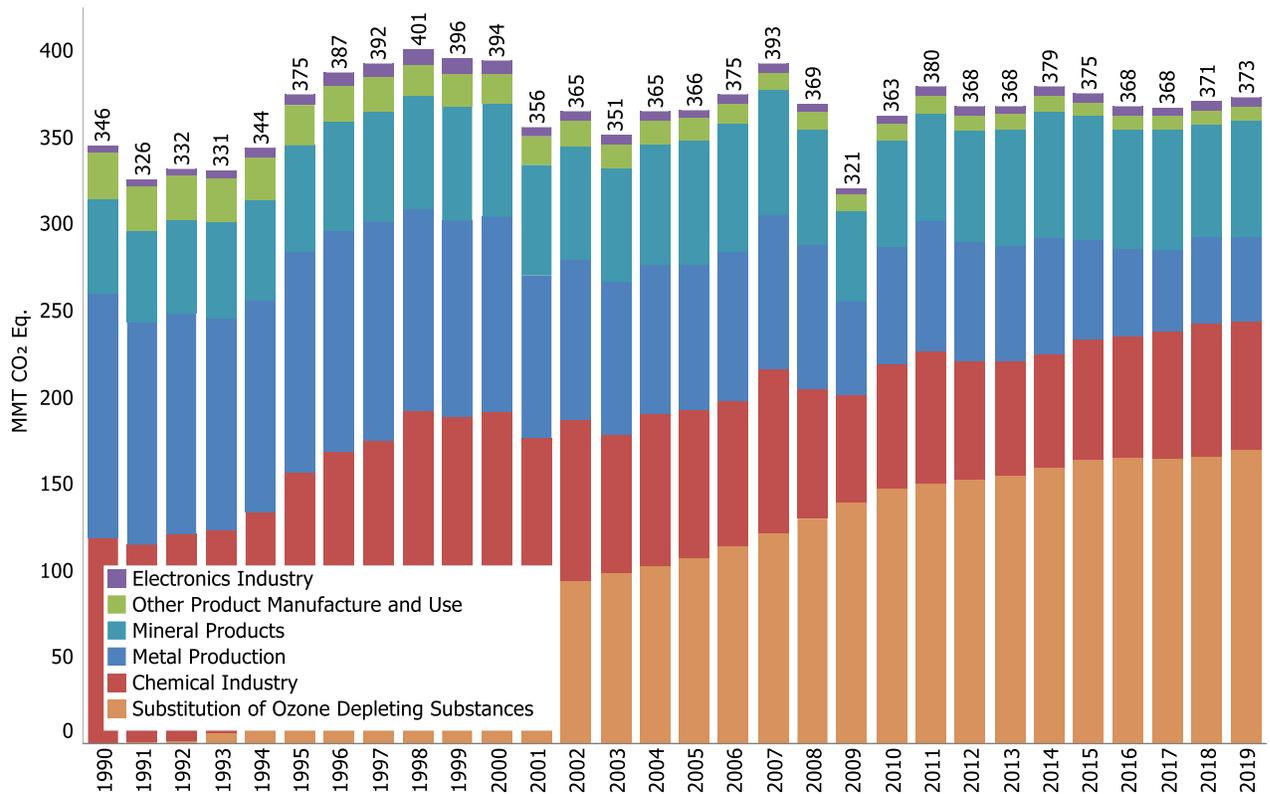
Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO$_2$ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO$_2$	**212.3**	**194.1**	**173.5**	**165.3**	**163.9**	**164.3**	**166.6**
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	47.9	43.6	40.6	42.6	41.3
Iron and Steel Production	*99.1*	*66.2*	*43.5*	*41.0*	*38.6*	*41.3*	*39.9*
Metallurgical Coke Production	*5.6*	*3.9*	*4.4*	*2.6*	*2.0*	*1.3*	*1.4*
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Petrochemical Production	21.6	27.4	28.1	28.3	28.9	29.3	30.8
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Aluminum Production	6.8	4.1	2.8	1.3	1.2	1.5	1.9
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2

Magnesium Production and Processing	+	+	+	+	+	+	+
CH₄	**0.3**	**0.1**	**0.2**	**0.3**	**0.3**	**0.3**	**0.4**
Petrochemical Production	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Ferroalloy Production	+	+	+	+	+	+	+
Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Iron and Steel Production	*+*	*+*	*+*	*+*	*+*	*+*	*+*
Metallurgical Coke Production	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
N₂O	**33.3**	**24.9**	**22.2**	**23.3**	**22.7**	**25.8**	**21.1**
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
N₂O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.2
HFCs	**46.5**	**127.5**	**168.3**	**168.1**	**170.3**	**169.8**	**174.6**
Substitution of Ozone Depleting Substances[a]	0.2	107.3	163.6	164.9	164.7	166.0	170.5
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Electronics Industry	0.2	0.2	0.3	0.3	0.4	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.2**	**4.4**	**4.1**	**4.7**	**4.5**
Electronics Industry	2.8	3.3	3.1	2.9	2.9	3.0	2.7
Aluminum Production	21.5	3.4	2.1	1.4	1.1	1.6	1.8
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	0.1	0.1
SF₆	**28.8**	**11.8**	**5.5**	**6.0**	**5.9**	**5.7**	**5.9**
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
Magnesium Production and Processing	5.2	2.7	1.0	1.1	1.0	1.0	0.9
Electronics Industry	0.5	0.7	0.7	0.8	0.7	0.8	0.8
NF₃	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Unspecified Mix of HFCs, NF₃, PFCs and SF₆	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+
Total	**345.6**	**365.7**	**375.4**	**368.0**	**367.7**	**371.3**	**373.7**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] Small amounts of PFC emissions also result from this source.

Overall, emissions from the IPPU sector increased by 8.1 percent from 1990 to 2019. Significant trends in emissions from IPPU source categories (Figure 2-11) over the thirty-year period from 1990 through 2019 included the following:

- HFC and PFC emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) have been increasing from small amounts in 1990 to 170.6 MMT CO_2 Eq. in 2019 and accounted for 45.6 percent of total IPPU emissions.

- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 3.1 percent to 41.3 MMT CO_2 Eq. from 2018 to 2019, and have declined overall by 63.4 MMT CO_2 Eq. (60.6 percent) from 1990 through 2019, due to restructuring of the industry. The trend in the United States has been a shift towards fewer integrated steel mills and more EAFs. EAFs use scrap steel as their main input and generally have less on-site emissions.

- Carbon dioxide emissions from petrochemicals increased by 42.5 percent between 1990 and 2019 from 21.6 MMT CO_2 Eq. to 30.8 MMT CO_2 Eq. The increase in emissions is largely driven by an almost doubling of production of ethylene over that time period.

- Carbon dioxide emissions from ammonia production (12.3 MMT CO_2 Eq. in 2019) decreased by 5.9 percent (0.8 MMT CO_2 Eq.) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia from year to year. Emissions from ammonia production have increased steadily since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities. Agricultural demands continue to drive demand for nitrogen fertilizers and the need for new ammonia production capacity.

- Carbon dioxide emissions from cement production increased by 22.1 percent (7.4 MMT CO_2 Eq.) from 1990 through 2019. They rose from 1990 through 2006 and then fell until 2009, due to a decrease in demand for construction materials during the economic recession. Since 2010, CO_2 emissions from cement production have risen 30.0 percent (9.4 MMT CO_2 Eq.).

- PFC emissions from aluminum production decreased by 91.8 percent (19.7 MMT CO_2 Eq.) from 1990 to 2019, due to both industry emission reduction efforts and lower domestic aluminum production.

Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane, N_2O, and CO_2 were the primary greenhouse gases emitted by agricultural activities. Carbon stock changes from agricultural soils are included in the LULUCF sector.

In 2019, agricultural activities were responsible for emissions of 628.6 MMT CO_2 Eq., or 9.6 percent of total U.S. greenhouse gas emissions. Methane emissions from enteric fermentation and manure management represented approximately 27.1 percent and 9.5 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2019. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2019, accounting for 75.4 percent. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.1 percent of total CO_2 emissions from anthropogenic activities. Figure 2-12 and Table 2-7 illustrate agricultural greenhouse gas emissions by source.

Figure 2-12: 2019 Agriculture Chapter Greenhouse Gas Sources
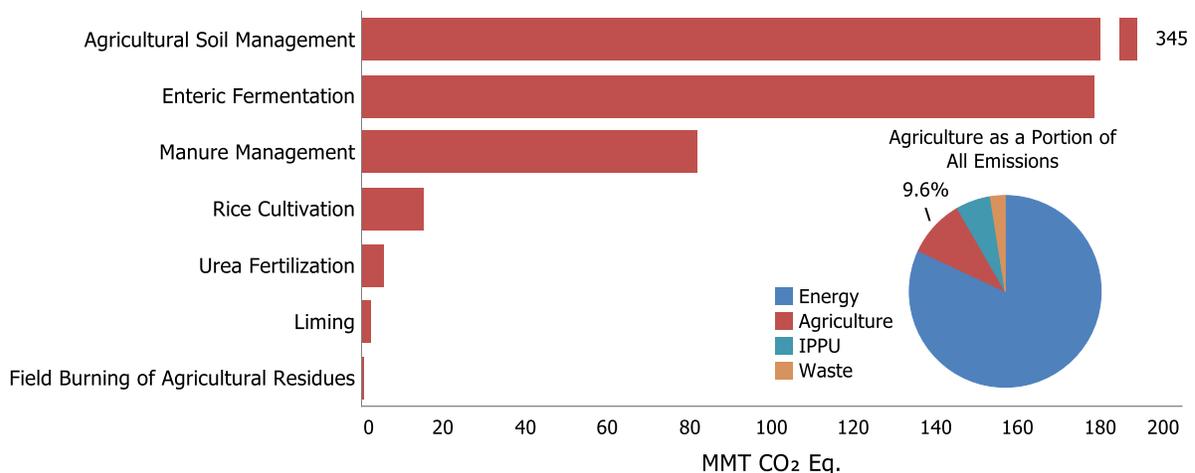
Figure 2-13: Trends in Agriculture Chapter Greenhouse Gas Sources
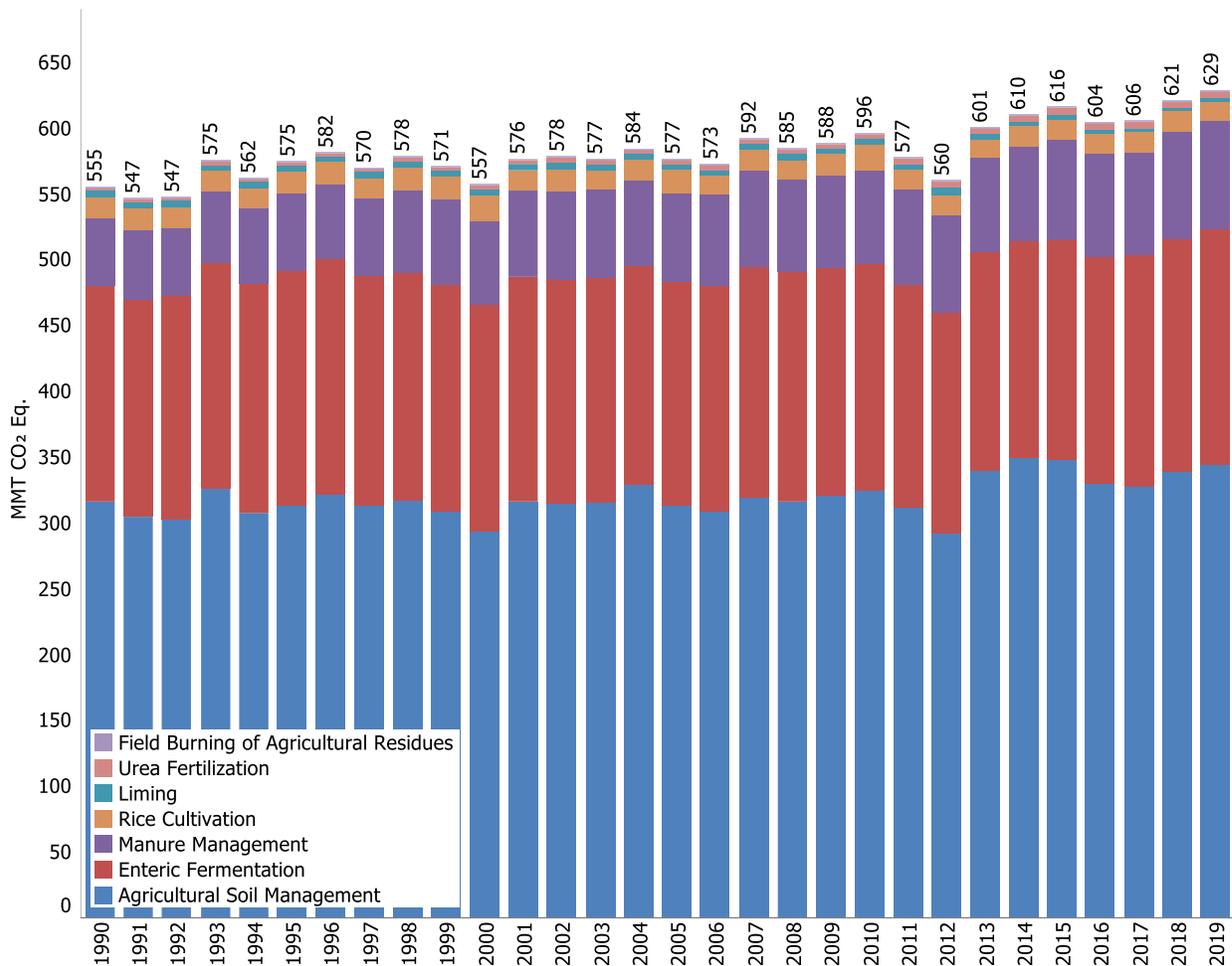
Table 2-7: Emissions from Agriculture (MMT CO₂ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO₂	**7.1**	**7.9**	**8.5**	**8.0**	**8.1**	**7.4**	**7.8**
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4
CH₄	**218.2**	**239.3**	**241.4**	**248.1**	**251.0**	**255.7**	**256.4**
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Manure Management	37.1	51.6	57.9	59.6	59.9	61.7	62.4
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N₂O	**330.1**	**329.9**	**366.2**	**348.4**	**346.4**	**357.9**	**364.4**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Manure Management	14.0	16.4	17.5	18.1	18.7	19.4	19.6
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**555.3**	**577.1**	**616.1**	**604.4**	**605.5**	**621.0**	**628.6**

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Agriculture source categories (Figure 2-13) over the thirty-year period from 1990 through 2019 included the following:

- Agricultural soils are the largest anthropogenic source of N_2O emissions in the United States, accounting for approximately 75.4 percent of N_2O emissions in 2019 and 5.3 percent of total emissions in the United States in 2019. Estimated emissions from this source in 2019 were 344.6 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2019, although overall emissions were 28.7 MMT CO_2 Eq. or 9.1 percent higher in 2019 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.

- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2019, enteric fermentation CH_4 emissions were 27.1 percent of total CH_4 emissions (178.6 MMT CO_2 Eq.), which represents an increase of 13.9 MMT CO_2 Eq. (8.4 percent) since 1990. This increase in emissions from 1990 to 2019 in enteric fermentation generally follows the increasing trends in cattle populations. For example, from 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2019, consistent with an increase in beef cattle population over those same years.

- Overall, emissions from manure management increased 60.3 percent between 1990 and 2019. This encompassed an increase of 67.9 percent for CH_4, from 37.1 MMT CO_2 Eq. in 1990 to 62.4 MMT CO_2 Eq. in 2019; and an increase of 40.2 percent for N_2O, from 14.0 MMT CO_2 Eq. in 1990 to 19.6 MMT CO_2 Eq. in 2019. The majority of the increase observed in CH_4 resulted from swine and dairy cattle manure, where emissions increased 48.6 and 117.3 percent, respectively, from 1990 to 2019. From 2018 to 2019, there was a 1.1 percent increase in total CH_4 emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

- Liming and urea fertilization are the only sources of CO_2 emissions reported in the Agriculture sector. All other CO_2 emissions and removals are characterized in the LULUCF sector. Estimated emissions from these sources were 2.4 and 5.3 MMT CO_2 Eq., respectively. Liming emissions increased by 8.6 percent relative to 2018 and decreased 2.2 MMT CO_2 Eq. or 47.7 percent relative to 1990, while urea fertilization emissions increased by 2.9 percent relative to 2018 and 2.9 MMT CO_2 Eq. or 121.0 percent relative to 1990.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon (C) stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (C sequestration) in the United States. The primary driver of fluxes on managed lands is from management of forest lands, but also includes trees in settlements (i.e., urban areas), afforestation, conversion of forest lands to settlements and croplands the management of croplands and grasslands, and the landfilling of yard trimmings and food scraps. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements,* is driven primarily by C stock gains in urban forests (i.e., Settlement Trees) through net tree growth and increased urban area, as well as long-term accumulation of C in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2019 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.7 MMT CO_2 Eq. (Table 2-8).[3] This represents an offset of approximately 12.3 percent of total (i.e., gross) greenhouse gas emissions in 2019. Emissions of CH_4 and N_2O from LULUCF activities in 2019 were 23.5 MMT CO_2 Eq. and represent 0.4 percent of total greenhouse gas emissions.[4] Between 1990 and 2019, total C sequestration in the LULUCF sector decreased by 10.6 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland*, as well as an increase in CO_2 emissions from *Land Converted to Settlements*.

Forest fires were the largest source of CH_4 emissions from LULUCF in 2019, totaling 9.5 MMT CO_2 Eq. (379 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8 MMT CO_2 Eq. (153 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). *Land Converted to Wetlands*, *Drained Organic Soils, and Peatlands Remaining Peatlands* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

Forest fires were also the largest source of N_2O emissions from LULUCF in 2019, totaling 6.2 MMT CO_2 Eq. (21 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2019 totaled to 2.4 MMT CO_2 Eq. (8 kt of N_2O). Additionally, the application of synthetic fertilizers to forest soils in 2019 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and *Drained Organic Soils* resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (0.5 kt of N_2O). *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Carbon dioxide removals from C stock changes are presented (green) in Figure 2-14. Figure 2-15 and Table 2-8 along with CH_4 and N_2O emissions (purple) for LULUCF source categories.

Figure 2-14: 2019 LULUCF Chapter Greenhouse Gas Sources and Sinks

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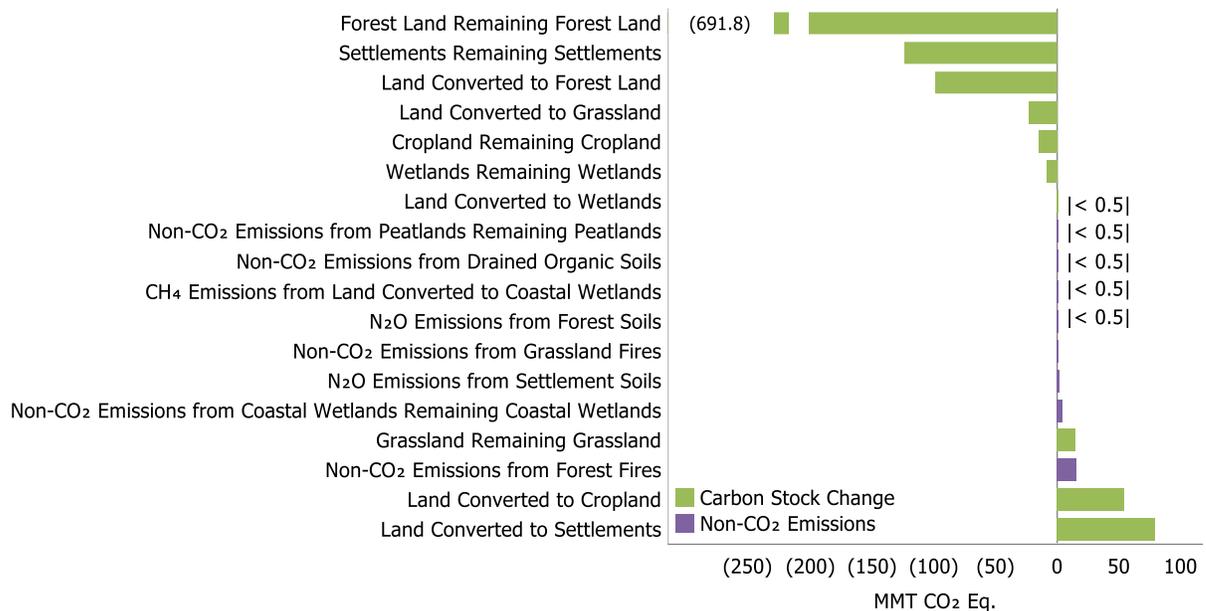
[3] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[4] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 2-15: Trends in Emissions and Removals (Net CO$_2$ Flux) from Land Use, Land-Use Change, and Forestry[a]
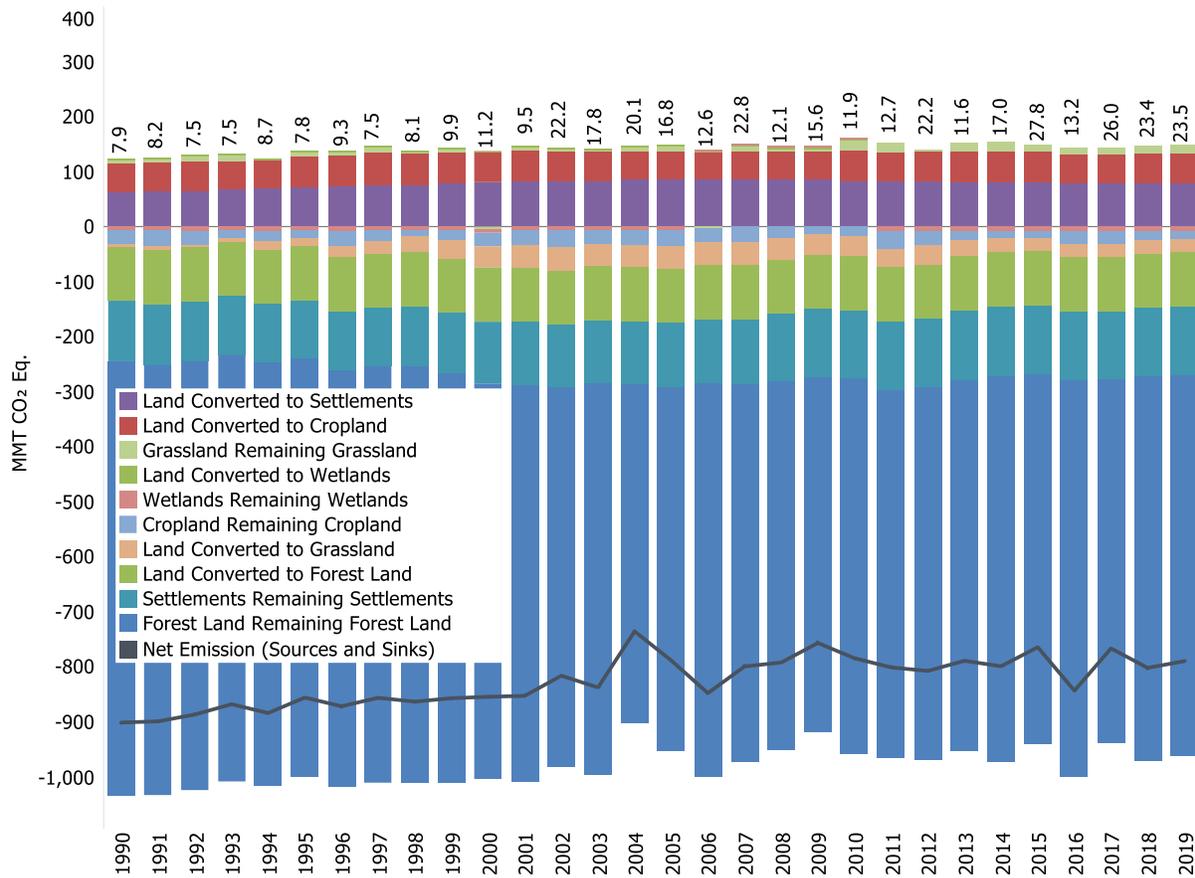
[a] In Figure 2-15, the values above stacked bars represent only non-CO$_2$ LULUCF emission. LULUCF emissions include the CH$_4$ and N$_2$O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and Coastal Wetlands Remaining Coastal Wetlands; CH$_4$ emissions from Land Converted to Coastal Wetlands; and N$_2$O emissions from Forest Soils and Settlement Soils

Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO$_2$ Eq.)

Land-Use Category	1990		2005		2015	2016	2017	2018	2019
Forest Land Remaining Forest Land	**(785.9)**		**(652.8)**		**(650.6)**	**(715.7)**	**(640.9)**	**(682.4)**	**(675.5)**
Changes in Forest Carbon Stocks[a]	(787.6)		(661.5)		(671.4)	(721.9)	(659.7)	(698.6)	(691.8)
Non-CO$_2$ Emissions from Forest Fires[b]	1.5		8.2		20.3	5.6	18.3	15.7	15.7
N$_2$O Emissions from Forest Soils[c]	0.1		0.5		0.5	0.5	0.5	0.5	0.5
Non-CO$_2$ Emissions from Drained Organic Soils[d]	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.2)**		**(98.7)**		**(98.9)**	**(99.0)**	**(99.1)**	**(99.1)**	**(99.1)**
Changes in Forest Carbon Stocks[e]	(98.2)		(98.7)		(98.9)	(99.0)	(99.1)	(99.1)	(99.1)
Cropland Remaining Cropland	**(23.2)**		**(29.0)**		**(12.8)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)		(29.0)		(12.8)	(22.7)	(22.3)	(16.6)	(14.5)
Land Converted to Cropland	**51.8**		**52.2**		**56.1**	**54.4**	**54.6**	**54.3**	**54.2**
Changes in all Ecosystem Carbon Stocks[f]	51.8		52.2		56.1	54.4	54.6	54.3	54.2
Grassland Remaining Grassland	**8.5**		**10.7**		**13.8**	**10.4**	**11.9**	**12.3**	**15.1**

Changes in Mineral and Organic Soil Carbon Stocks	8.3	10.0	13.1	9.8	11.3	11.7	14.5
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.7	0.7	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(6.2)**	**(40.1)**	**(23.9)**	**(24.0)**	**(24.4)**	**(24.1)**	**(23.2)**
Changes in all Ecosystem Carbon Stocks[f]	(6.2)	(40.1)	(23.9)	(24.0)	(24.4)	(24.1)	(23.2)
Wetlands Remaining Wetlands	**(3.5)**	**(2.6)**	**(4.1)**	**(4.1)**	**(4.0)**	**(4.0)**	**(4.0)**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.8	0.7	0.8	0.8	0.8
Changes in Aboveground and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands	**0.7**	**0.7**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Changes in Aboveground and Soil Carbon Stocks	0.4	0.4	(0.1)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(123.7)**	**(121.5)**	**(121.4)**	**(121.2)**	**(121.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	15.7	16.0	16.0	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(130.4)	(129.8)	(129.8)	(129.8)	(129.8)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(11.1)	(10.0)	(9.8)	(9.8)	(10.2)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.2	2.3	2.4	2.4
Land Converted to Settlements	**62.9**	**85.0**	**80.1**	**79.4**	**79.3**	**79.3**	**79.2**
Changes in all Ecosystem Carbon Stocks[f]	62.9	85.0	80.1	79.4	79.3	79.3	79.2
LULUCF Carbon Stock Change[i]	**(908.7)**	**(804.8)**	**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
LULUCF Emissions[j]	**7.9**	**16.8**	**27.8**	**13.2**	**26.0**	**23.4**	**23.5**
LULUCF CH_4 Emissions	5.0	9.3	16.6	7.7	15.3	13.8	13.8
LULUCF N_2O Emissions	3.0	7.5	11.3	5.5	10.6	9.7	9.7
LULUCF Sector Net Total[k]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[g] Estimates include CH_4 and N_2O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements* because it is not possible to separate the activity data at this time.

[i] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Other significant trends from 1990 to 2019 in emissions from LULUCF categories (Figure 2-15) over the thirty-year period from 1990 through 2019 included the following:

- Annual carbon (C) sequestration by forest land (i.e., annual C stock accumulation in the five ecosystem C pools and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) has decreased by approximately 10.7 percent since 1990. This is primarily due to decreased C stock gains in *Land Converted to Forest Land* and the harvested wood products pools within *Forest Land Remaining Forest Land*.

- Annual C sequestration from *Settlements Remaining Settlements* (which includes organic soils, settlement trees, and landfilled yard trimmings and food scraps) has increased by 13.2 percent over the period from 1990 to 2019. This is primarily due to an increase in urbanized land area in the United States with trees growing on it.

- Annual emissions from *Land Converted to Settlements* increased by approximately 26.0 percent from 1990 to 2019 due primarily to C stock losses from *Forest Land Converted to Settlements* and mineral soils C stocks from *Grassland Converted to Settlements*.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-16). In 2019, landfills were the third-largest source of U.S. anthropogenic CH_4 emissions, generating 114.5 MMT CO_2 Eq. and accounting for 17.4 percent of total U.S. CH_4 emissions.[5] Additionally, wastewater treatment generates emissions of 44.8 MMT CO_2 Eq. and accounts for 27.3 percent of waste emissions, 2.8 percent of U.S. CH_4 emissions, and 5.8 percent of U.S. N_2O emissions. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.3 MMT CO_2 Eq. and 2.0 MMT CO_2 Eq., respectively. Overall, emission sources accounted for in the Waste chapter generated 163.7 MMT CO_2 Eq., or 2.5 percent of total U.S. greenhouse gas emissions in 2019. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-9.

Figure 2-16: 2019 Waste Sector Greenhouse Gas Sources

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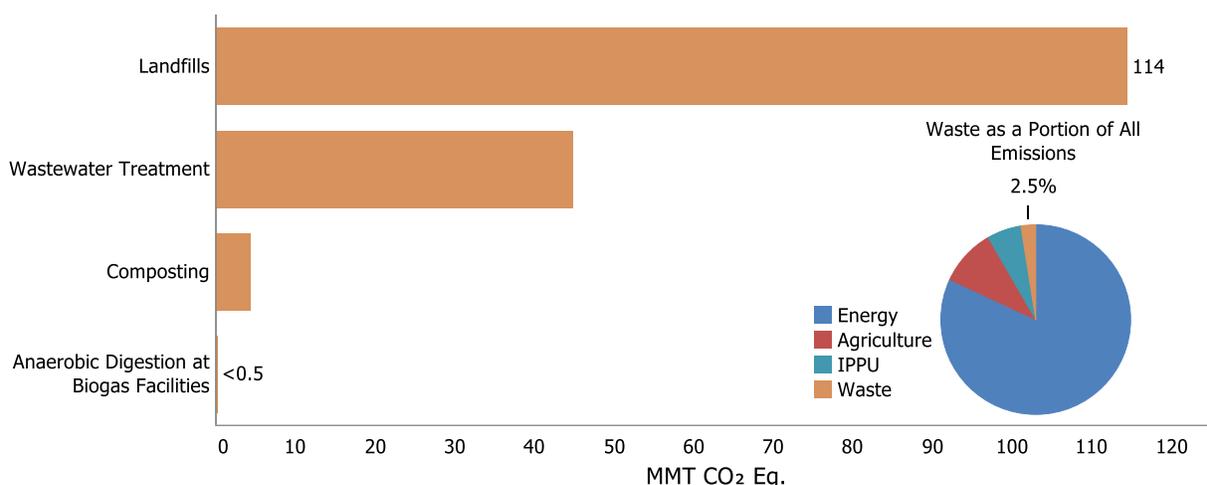
[5] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

Figure 2-17: Trends in Waste Chapter Greenhouse Gas Sources
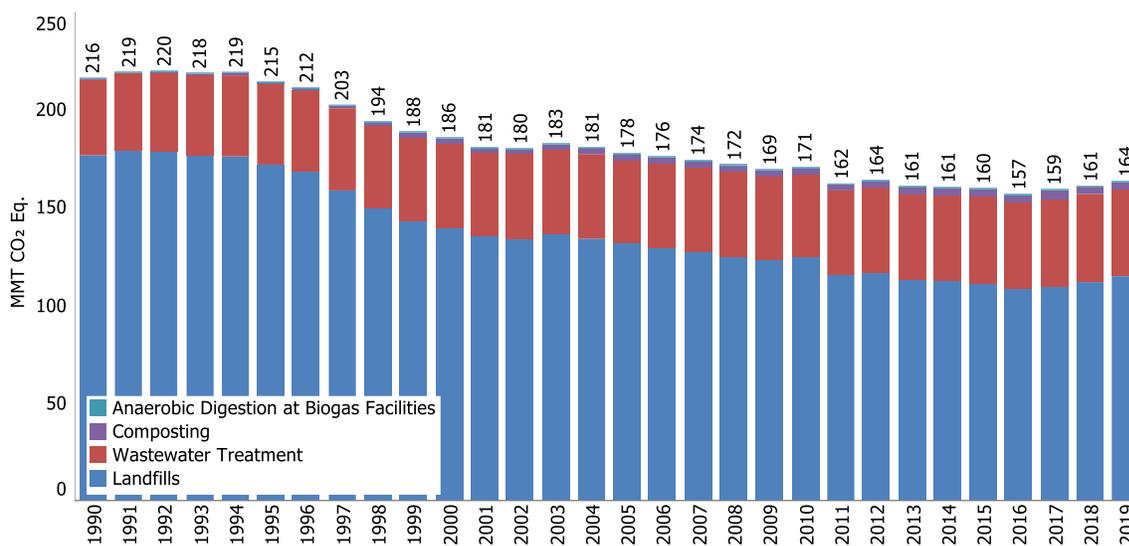
Table 2-9: Emissions from Waste (MMT CO$_2$ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CH$_4$	**197.1**	**153.4**	**132.5**	**129.2**	**130.5**	**132.9**	**135.3**
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Wastewater Treatment	20.2	20.1	18.8	18.7	18.5	18.4	18.4
Composting	0.4	1.9	2.1	2.3	2.4	2.3	2.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
N$_2$O	**19.0**	**24.6**	**27.3**	**27.9**	**28.6**	**28.2**	**28.4**
Wastewater Treatment	18.7	23.0	25.4	25.9	26.4	26.1	26.4
Composting	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Total	**216.2**	**178.0**	**159.8**	**157.1**	**159.0**	**161.1**	**163.7**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO$_2$ Eq.

Some significant trends in U.S. emissions from waste source categories (Figure 2-17) over the thirty-year period from 1990 through 2019 included the following:

- From 1990 to 2019, net CH$_4$ emissions from landfills decreased by 62.1 MMT CO$_2$ Eq. (35.2 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.

- From 1990 to 2019, CH$_4$ and N$_2$O emissions from wastewater treatment decreased by 1.8 MMT CO$_2$ Eq. (8.7 percent) and increased by 7.7 MMT CO$_2$ Eq. (41.0 percent), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

- Combined CH$_4$ and N$_2$O emissions from composting have generally increased approximately 3.6 MMT CO$_2$ Eq. since 1990, from 0.7 MMT CO$_2$ Eq. to 4.3 MMT CO$_2$ Eq. in 2019, which represents more than a five-fold

increase over the time series. The growth in composting since the 1990s is attributable to primarily four factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills; (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts; (3) an increased awareness of the environmental benefits of composting; and (4) loans or grant programs to establish or expand composting infrastructure.

2.2 Emissions by Economic Sector

Throughout this report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC and detailed above: Energy, IPPU, Agriculture, LULUCF, and Waste. It is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. See Box 2-1 for more information on how economic sectors are defined. For more information on trends in the Land Use, Land Use Change, and Forestry sector, see Section 2.1.

Using this categorization, transportation activities, in aggregate, accounted for the largest portion (28.6 percent) of total U.S. greenhouse gas emissions in 2019. Emissions from electric power accounted for the second largest portion (25.1 percent), while emissions from industry accounted for the third largest portion (22.9 percent) of total U.S. greenhouse gas emissions in 2019. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 23.3 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for roughly 10.2 percent of emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for roughly 6.9 percent and 5.8 percent of greenhouse gas emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered (in the form of C) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands. Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-18 shows the trend in emissions by sector from 1990 to 2019.

Figure 2-18: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors
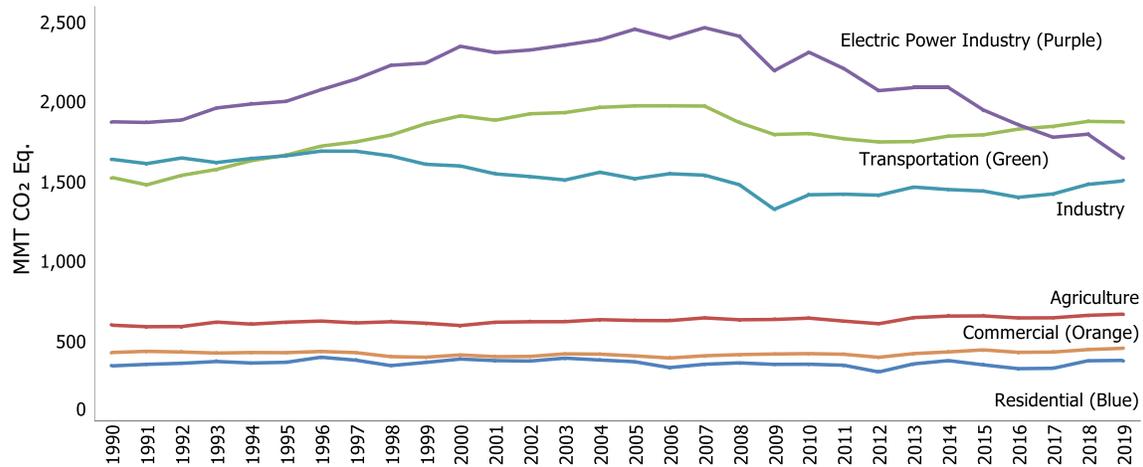
Note: Emissions and removals from Land Use, Land Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO$_2$ Eq. and Percent of Total in 2019)

Sector/Source	1990	2005	2015	2016	2017	2018	2019	Percent[a]
Transportation	**1,526.6**	**1,975.6**	**1,794.1**	**1,830.0**	**1,847.3**	**1,878.2**	**1,875.7**	**28.6%**
CO$_2$ from Fossil Fuel Combustion	1,469.1	1,858.6	1,719.2	1,759.9	1,782.4	1,816.6	1,817.2	27.7%
Substitution of Ozone Depleting Substances	+	69.3	46.3	43.3	40.1	38.5	36.7	0.6%
Mobile Combustion	45.7	37.5	17.5	16.4	15.2	14.0	12.9	0.2%
Non-Energy Use of Fuels	11.8	10.2	11.0	10.4	9.6	9.2	8.9	0.1%
Electric Power Industry	**1,875.7**	**2,456.3**	**1,950.0**	**1,857.6**	**1,778.9**	**1,798.0**	**1,648.1**	**25.1%**
CO$_2$ from Fossil Fuel Combustion	1,820.0	2,400.1	1,900.6	1,808.9	1,732.0	1,752.9	1,606.0	24.5%
Stationary Combustion	20.9	30.9	27.7	27.4	25.9	25.6	22.3	0.3%
Incineration of Waste	8.5	13.1	11.8	11.8	11.8	11.9	11.8	0.2%
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2	0.1%
Other Process Uses of Carbonates	3.1	3.8	6.1	5.5	5.0	3.7	3.7	0.1%
Industry	**1,640.7**	**1,518.8**	**1,441.6**	**1,402.2**	**1,423.4**	**1,483.3**	**1,504.8**	**22.9%**
CO$_2$ from Fossil Fuel Combustion	810.4	802.1	756.1	752.3	750.3	773.8	782.8	11.9%
Natural Gas Systems	219.0	189.4	179.0	177.4	179.9	186.4	194.9	3.0%
Non-Energy Use of Fuels	97.6	111.4	96.8	88.8	103.3	119.8	119.2	1.8%
Petroleum Systems	58.6	51.5	73.9	61.1	64.4	74.5	86.4	1.3%
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4	0.7%
Iron and Steel Production	104.8	70.1	47.9	43.6	40.6	42.6	41.3	0.6%
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9	0.6%
Substitution of Ozone Depleting Substances	+	8.7	27.6	29.7	31.6	33.1	34.3	0.5%
Petrochemical Production	21.8	27.5	28.2	28.6	29.2	29.6	31.1	0.5%
Landfills (Industrial)	10.9	14.4	15.0	15.0	15.0	15.0	15.1	0.2%
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3	0.2%
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1	0.2%
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0	0.2%

Wastewater Treatment (Industrial)	5.8	6.4	6.4	6.6	6.7	6.8	6.9	0.1%
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6	0.1%
Mobile Combustion	4.0	6.2	5.6	5.7	6.0	6.1	6.3	0.1%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2	0.1%
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9	0.1%
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3	0.1%
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9	0.1%
Electronics Industry	3.6	4.8	5.0	5.0	4.9	5.1	4.6	0.1%
N$_2$O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	0.1%
Stationary Combustion	4.9	4.7	4.2	4.2	4.1	4.1	4.0	0.1%
Other Process Uses of Carbonates	3.1	3.8	6.1	5.5	5.0	3.7	3.7	0.1%
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7	0.1%
Aluminum Production	28.3	7.6	4.9	2.7	2.3	3.1	3.6	0.1%
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8	+%
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6	+%
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5	+%
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4	+%
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3	+%
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0	+%
Magnesium Production and Processing	5.2	2.7	1.1	1.2	1.1	1.1	1.0	+%
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5	+%
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**600.2**	**629.7**	**658.5**	**645.8**	**646.6**	**662.0**	**669.5**	**10.2%**
N$_2$O from Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6	5.3%
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6	2.7%
Manure Management	51.1	67.9	75.4	77.7	78.5	81.1	82.0	1.3%
CO$_2$ from Fossil Fuel Combustion	43.4	50.8	41.1	40.2	39.8	39.8	39.7	0.6%
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1	0.2%
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3	0.1%
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4	+%
Mobile Combustion	1.5	1.8	1.2	1.2	1.2	1.2	1.2	+%
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6	+%
Stationary Combustion	+	+	+	+	+	+	+	+%
Commercial	**429.2**	**407.9**	**445.4**	**430.1**	**431.9**	**447.3**	**455.3**	**6.9%**
CO$_2$ from Fossil Fuel Combustion	228.3	227.1	244.6	231.6	232.0	245.7	249.7	3.8%
Landfills (Municipal)	165.7	117.0	96.4	93.1	94.4	97.0	99.4	1.5%
Substitution of Ozone Depleting Substances	+	22.1	60.8	61.5	61.0	60.8	62.3	0.9%
Wastewater Treatment (Domestic)	33.0	36.6	37.8	38.0	38.2	37.8	37.9	0.6%
Composting	0.7	3.5	4.0	4.3	4.6	4.3	4.3	0.1%
Stationary Combustion	1.5	1.4	1.6	1.5	1.5	1.6	1.6	+%
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2	+%
Residential	**345.1**	**371.0**	**351.5**	**327.8**	**329.9**	**377.3**	**379.5**	**5.8%**
CO$_2$ from Fossil Fuel Combustion	338.6	358.9	317.3	292.8	293.4	338.1	336.8	5.1%

Substitution of Ozone Depleting Substances	0.2	7.2	28.9	30.4	32.0	33.8	37.2	0.6%
Stationary Combustion	6.3	4.9	5.3	4.7	4.5	5.4	5.5	0.1%
U.S. Territories	**25.2**	**63.7**	**30.0**	**26.8**	**25.4**	**25.4**	**25.4**	**0.4%**
CO$_2$ from Fossil Fuel Combustion	21.7	55.9	29.2	26.0	24.6	24.6	24.6	0.4%
Non-Energy Use of Fuels	3.4	7.6	0.7	0.7	0.7	0.7	0.7	+%
Stationary Combustion	0.1	0.2	0.1	0.1	0.1	0.1	0.1	+%
Total Emissions (Sources)	6,442.7	7,423.0	6,671.1	6,520.3	6,483.3	6,671.4	6,558.3	100.0%
LULUCF Sector Net Total[b]	(900.8)	788.1)	(763.8)	(842.8)	(766.1)	(801.4)	(789.2)	(12.0%)
Net Emissions (Sources and Sinks)	5,541.9	6,635.0	5,907.3	5,677.5	5,717.2	5,870.0	5,769.1	88.0%

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

+ Does not exceed 0.05 MMT CO$_2$ Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2019.

[b] The LULUCF Sector Net Total is the net sum of all LULUCF CH$_4$ and N$_2$O emissions to the atmosphere plus net carbon stock changes.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the Economic Sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the Inventory expands upon the standard IPCC sectors common for UNFCCC reporting. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The *Electric Power* economic sector includes CO$_2$, CH$_4$ and N$_2$O emissions from the combustion of fossil fuels that are included in the EIA electric power sector. Carbon dioxide, CH$_4$, and N$_2$O emissions from waste incineration are included in the Electric Power economic sector, as the majority of municipal solid waste is combusted in plants that produce electricity. The Electric Power economic sector also includes SF$_6$ from Electrical Transmission and Distribution, and a portion of CO$_2$ from Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

The *Transportation* economic sector includes CO$_2$ emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH$_4$ and N$_2$O from mobile combustion are also apportioned to the Transportation economic sector based on the EIA transportation fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO$_2$ emissions from Non-Energy Uses of Fossil Fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

The *Industry* economic sector includes CO$_2$ emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH$_4$ and N$_2$O emissions from stationary and mobile combustion are also apportioned to the Industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the Agriculture economic sector. Substitution of Ozone Depleting Substances emissions are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector. Finally, CH$_4$ emissions from industrial landfills and CH$_4$ and N$_2$O from industrial wastewater treatment are included in the Industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the Industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as Cement Production, Iron and Steel Production and Metallurgical Coke Production, and Ammonia Production. Additionally, fugitive emissions from energy production sources, such as Natural Gas Systems, Coal Mining, and Petroleum Systems are included in the Industry economic sector. A portion of CO$_2$ from Other Process Uses of Carbonates (from pollution control equipment installed in large industrial facilities) is also included in the Industry economic sector. Finally, all remaining CO$_2$ emissions from Non-Energy Uses of Fossil Fuels are assumed

to be industrial in nature (besides the lubricants for transportation vehicles specified above) and are attributed to the Industry economic sector.

The *Agriculture* economic sector includes CO_2 emissions from the combustion of fossil fuels that are based on supplementary sources of agriculture fuel use data, because EIA does not include an agriculture fuel-consuming sector. Agriculture equipment is included in the EIA industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with separate EIA fuel sales reports (USDA 2019; EIA 2020a). These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. CO_2 emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the Agriculture economic sector based on agricultural fuel use.

The other IPCC Agriculture emission source categories apportioned to the Agriculture economic sector include N_2O emissions from Agricultural Soils, CH_4 from Enteric Fermentation, CH_4 and N_2O from Manure Management, CH_4 from Rice Cultivation, CO_2 emissions from Liming and Urea Application, and CH_4 and N_2O from Field Burning of Agricultural Residues.

The *Residential* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Substitution of Ozone Depleting Substances are apportioned to the Residential economic sector based on emissions from residential air-conditioning systems. Nitrous oxide emissions from the application of fertilizers to developed land (termed "settlements" by the IPCC) are also included in the Residential economic sector.

The *Commercial* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from Mobile Combustion are also apportioned to the Commercial economic sector based on the EIA commercial fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources, including direct CH_4 from municipal landfills, CH_4 from anaerobic digestion at biogas facilities, CH_4 and N_2O from domestic wastewater treatment, and composting, are also included in the Commercial economic sector.

Emissions with Electricity Distributed to Economic Sectors

It is also useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power are allocated to the economic sectors in which the electricity is used).

The generation, transmission, and distribution of electricity accounted for 25.1 percent of total U.S. greenhouse gas emissions in 2019. Electric power-related emissions decreased by 12.1 percent since 1990 and by 8.3 percent from 2018 to 2019, primarily due to a significantly colder winter and a hotter summer in 2019 compared to 2018, which increased the amount of energy required for heating and cooling. Between 2018 to 2019, the consumption of natural gas for electric power generation increased by 6.7, while the consumption of coal and petroleum decreased by 15.5 and 27.6 percent, respectively, reflecting a continued shift from coal to natural gas for electricity generation.

From 2018 to 2019, electricity sales to the residential and commercial end-use sectors decreased by 2.0 percent and 1.5 percent, respectively. Electricity sales to the industrial sector increased by approximately 0.2 percent. Overall, from 2018 to 2019, the amount of electricity retail sales (in kWh) decreased by 1.2 percent. Table 2-11 provides a detailed summary of emissions from electric power-related activities.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2015	2016	2017	2018	2019
CO_2	**1,831.2**	**2,416.6**	**1,918.3**	**1,825.9**	**1,748.5**	**1,768.2**	**1,621.2**
Fossil Fuel Combustion	1,820.0	2,400.1	1,900.6	1,808.9	1,732.0	1,752.9	1,606.0
Coal	*1,546.5*	*1,982.8*	*1,351.4*	*1,242.0*	*1,207.1*	*1,152.9*	*973.5*
Natural Gas	*175.4*	*318.9*	*525.2*	*545.0*	*505.6*	*577.4*	*616.0*
Petroleum	*97.5*	*98.0*	*23.7*	*21.5*	*18.9*	*22.2*	*16.2*
Geothermal	*0.5*	*0.5*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	8.1	12.7	11.5	11.5	11.5	11.5	11.5
Other Process Uses of Carbonates	3.1	3.8	6.1	5.5	5.0	3.7	3.7
CH_4	**0.4**	**0.9**	**1.2**	**1.2**	**1.1**	**1.2**	**1.3**
Stationary Sources[a]	0.4	0.9	1.2	1.2	1.1	1.2	1.3
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**21.0**	**30.4**	**26.8**	**26.5**	**25.1**	**24.7**	**21.4**
Stationary Sources[a]	20.5	30.1	26.5	26.2	24.8	24.4	21.1
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
SF_6	**23.2**	**8.4**	**3.8**	**4.1**	**4.2**	**3.9**	**4.2**
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
Total	**1,875.7**	**2,456.3**	**1,950.0**	**1,857.6**	**1,778.9**	**1,798.0**	**1,648.1**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes only stationary combustion emissions related to the generation of electricity.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2020b; Duffield 2006). These source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, Incineration of Waste, Other Process Uses of Carbonates, and SF_6 from Electrical Transmission and Distribution Systems. Note that only 50 percent of the Other Process Uses of Carbonates emissions were associated with electric power and distributed as described; the remainder of Other Process Uses of Carbonates emissions were attributed to the industrial processes economic end-use sector.[6]

When emissions from electricity use are distributed among these economic end-use sectors, industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.7 percent), followed closely by emissions from transportation (28.7 percent). Emissions from the commercial and residential sectors also increase substantially when emissions from electricity are included (15.6 and 14.9 percent, respectively). In all economic end-use sectors except agriculture, CO_2 accounts for more than 79.0 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-19 shows the trend in these emissions by sector from 1990 to 2019.

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[6] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Figure 2-19: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors
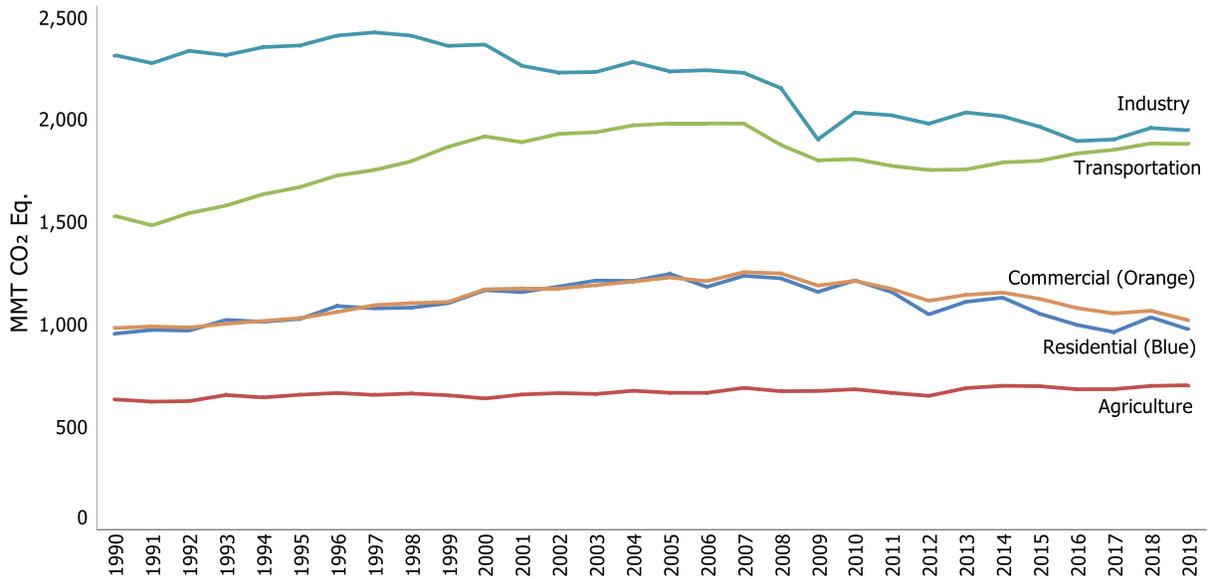
Note: Emissions and removals from Land Use, Land Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO$_2$ Eq.) and Percent of Total in 2019

Sector/Gas	1990	2005	2015	2016	2017	2018	2019	Percent[a]
Industry	**2,313.1**	**2,234.1**	**1,964.2**	**1,894.6**	**1,902.7**	**1,958.3**	**1,947.2**	**29.7%**
Direct Emissions	**1,640.7**	**1,518.8**	**1,441.6**	**1,402.2**	**1,423.4**	**1,483.3**	**1,504.8**	**22.9%**
CO$_2$	1,158.9	1,140.9	1,081.9	1,052.8	1,068.6	1,125.2	1,149.4	17.5%
CH$_4$	365.2	304.4	289.7	278.1	280.2	280.0	280.7	4.3%
N$_2$O	40.3	33.8	30.2	31.5	30.9	34.2	29.6	0.5%
HFCs, PFCs, SF$_6$, and NF$_3$	76.3	39.6	39.8	39.9	43.6	43.9	45.2	0.7%
Electricity-Related	**672.4**	**715.3**	**522.6**	**492.4**	**479.3**	**475.0**	**442.4**	**6.7%**
CO$_2$	656.4	703.7	514.1	484.0	471.1	467.2	435.2	6.6%
CH$_4$	0.2	0.3	0.3	0.3	0.3	0.3	0.3	+%
N$_2$O	7.5	8.9	7.2	7.0	6.8	6.5	5.7	0.1%
SF$_6$	8.3	2.4	1.0	1.1	1.1	1.0	1.1	+%
Transportation	**1,529.8**	**1,980.4**	**1,798.4**	**1,834.3**	**1,851.8**	**1,883.0**	**1,880.6**	**28.7%**
Direct Emissions	**1,526.6**	**1,975.6**	**1,794.1**	**1,830.0**	**1,847.3**	**1,878.2**	**1,875.7**	**28.6%**
CO$_2$	1,481.0	1,868.8	1,730.2	1,770.2	1,792.0	1,825.8	1,826.1	27.8%
CH$_4$	5.7	3.0	1.8	1.7	1.6	1.5	1.4	+%
N$_2$O	39.9	34.5	15.8	14.8	13.6	12.4	11.5	0.2%
HFCs[b]	+	69.3	46.3	43.3	40.1	38.5	36.7	0.6%
Electricity-Related	**3.1**	**4.8**	**4.4**	**4.3**	**4.4**	**4.8**	**4.9**	**0.1%**
CO$_2$	3.1	4.8	4.3	4.2	4.4	4.7	4.8	0.1%
CH$_4$	+	+	+	+	+	+	+	+%
N$_2$O	+	0.1	0.1	0.1	0.1	0.1	0.1	+%
SF$_6$	+	+	+	+	+	+	+	+%
Commercial	**983.4**	**1,229.8**	**1,125.7**	**1,080.8**	**1,054.5**	**1,067.8**	**1,022.3**	**15.6%**
Direct Emissions	**429.2**	**407.9**	**445.4**	**430.1**	**431.9**	**447.3**	**455.3**	**6.9%**
CO$_2$	228.3	227.1	244.6	231.6	232.0	245.7	249.7	3.8%
CH$_4$	181.9	134.2	112.9	109.3	110.5	112.9	115.2	1.8%
N$_2$O	19.0	24.5	27.1	27.7	28.4	27.9	28.2	0.4%
HFCs	+	22.1	60.8	61.5	61.0	60.8	62.3	0.9%

Electricity-Related	**554.2**	**821.8**	**680.3**	**650.7**	**622.6**	**620.4**	**566.9**	**8.6%**
CO_2	541.0	808.5	669.2	639.6	612.0	610.1	557.7	8.5%
CH_4	0.1	0.3	0.4	0.4	0.4	0.4	0.4	+%
N_2O	6.2	10.2	9.4	9.3	8.8	8.5	7.4	0.1%
SF_6	6.8	2.8	1.3	1.4	1.5	1.3	1.5	+%
Residential	**956.0**	**1,247.1**	**1,053.1**	**998.9**	**963.7**	**1,035.9**	**978.3**	**14.9%**
Direct Emissions	**345.1**	**371.0**	**351.5**	**327.8**	**329.9**	**377.3**	**379.5**	**5.8%**
CO_2	338.6	358.9	317.3	292.8	293.4	338.1	336.8	5.1%
CH_4	5.2	4.1	4.5	3.9	3.8	4.5	4.6	0.1%
N_2O	1.0	0.9	0.9	0.8	0.7	0.9	0.9	+%
HFCs	0.2	7.2	28.9	30.4	32.0	33.8	37.2	0.6%
Electricity-Related	**610.9**	**876.1**	**701.6**	**671.1**	**633.8**	**658.7**	**598.8**	**9.1%**
CO_2	596.4	861.9	690.1	659.6	623.0	647.7	589.0	9.0%
CH_4	0.1	0.3	0.4	0.4	0.4	0.4	0.5	+%
N_2O	6.8	10.9	9.7	9.6	8.9	9.1	7.8	0.1%
SF_6	7.5	3.0	1.4	1.5	1.5	1.4	1.5	+%
Agriculture	**635.3**	**668.0**	**699.7**	**684.9**	**685.3**	**701.1**	**704.6**	**10.7%**
Direct Emissions	**600.2**	**629.7**	**658.5**	**645.8**	**646.6**	**662.0**	**669.5**	**10.2%**
CO_2	50.5	58.7	49.6	48.1	47.9	47.3	47.4	0.7%
CH_4	218.3	239.5	241.5	248.2	251.1	255.8	256.5	3.9%
N_2O	331.4	331.5	367.3	349.5	347.5	358.9	365.5	5.6%
Electricity-Related	**35.1**	**38.3**	**41.3**	**39.1**	**38.7**	**39.1**	**35.2**	**0.5%**
CO_2	34.2	37.7	40.6	38.5	38.1	38.5	34.6	0.5%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.4	0.5	0.6	0.6	0.5	0.5	0.5	+%
SF_6	0.4	0.1	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**25.2**	**63.7**	**30.0**	**26.8**	**25.4**	**25.4**	**25.4**	**0.4%**
Total Emissions (Sources)	**6,442.7**	**7,423.0**	**6,671.1**	**6,520.3**	**6,483.3**	**6,671.4**	**6,558.3**	**100.0%**
LULUCF Sector Net Total[c]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**	**(+)%**
Net Emissions (Sources and Sinks)	**5,541.9**	**6,635.0**	**5,907.3**	**5,677.5**	**5,717.2**	**5,870.0**	**5,769.1**	**88.0%**

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for year 2019.

[b] Includes primarily HFC-134a.

[c] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Industry

The industry end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate, and with the distribution of electricity-related emissions, accounts for 29.7 percent of U.S. greenhouse gas emissions in 2019. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 emissions from coal mining, byproduct CO_2 emissions from cement manufacture, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

Since 1990, industrial sector emissions have declined by 15.8 percent. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy thatled to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 28.7 percent of U.S. greenhouse gas emissions in 2019. The largest sources of transportation greenhouse gas emissions in 2019 were passenger cars (40.5 percent); freight trucks (23.6 percent); light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.2 percent); commercial aircraft (7.2 percent); pipelines (2.9 percent); other aircraft (2.4 percent); rail (2.2 percent); and ships and boats (2.1 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation, indirect emissions from electricity use and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

In terms of the overall trend, from 1990 to 2019, total transportation emissions increased due, in large part, to increased demand for travel. The number of VMT by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47.5 percent from 1990 to 2019, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013,[7] then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2016, the rate of light-duty VMT growth has slowed to less than one percent each year. Average new vehicle fuel economy has increased almost every year since 2005, while light-duty truck market share decreased to about 33 percent in 2009 and has since varied from year to year between 36 and 56 percent. Light-duty truck market share was about 56 percent of new vehicles in model year 2019 (EPA 2020a).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals. Historically, the majority of electricity use in the transportation sector was for rail transport. However, more recently there has been increased electricity use in on-road electric and plug-in hybrid vehicles. For a more detailed breakout of emissions by fuel type by vehicle see Table A-104 in Annex 3.

Almost all of the energy used for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 24 percent from 1990 to 2019.[8] This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 36.7 MMT CO_2 Eq. in 2019, led to an increase in overall greenhouse gas emissions from transportation activities of 23 percent.[9]

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[7] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2018). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2018 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

[8] See previous footnote.

[9] See previous footnote.

Figure 2-20: Trends in Transportation-Related Greenhouse Gas Emissions[10]
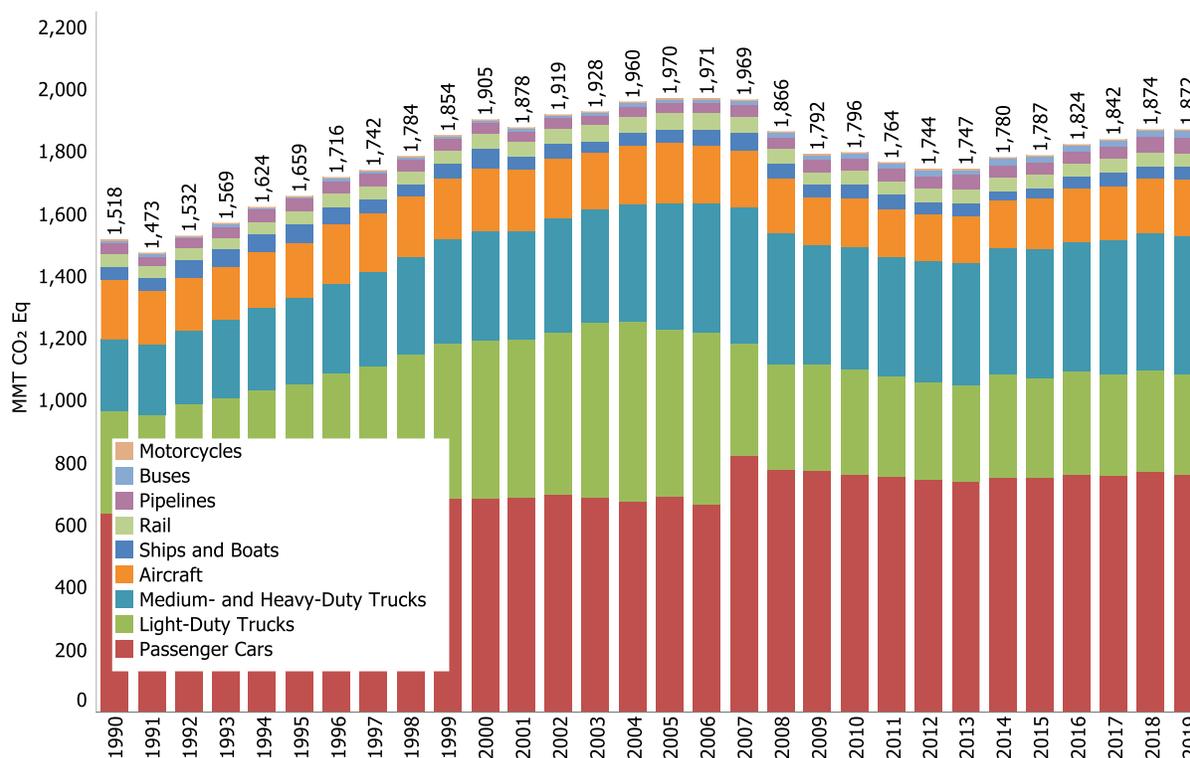
Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO₂ Eq.)

Gas/Vehicle	1990	2005	2015	2016	2017	2018	2019
Passenger Cars	**639.6**	**691.7**	**752.5**	**763.5**	**760.6**	**770.3**	**762.3**
CO_2	612.2	641.4	729.1	742.7	742.5	754.3	748.3
CH_4	3.2	1.3	0.6	0.6	0.5	0.5	0.4
N_2O	24.1	17.3	8.1	7.1	6.1	5.1	4.4
HFCs	0.0	31.7	14.7	13.2	11.4	10.4	9.3
Light-Duty Trucks	**326.7**	**537.7**	**320.9**	**330.2**	**324.3**	**325.7**	**323.1**
CO_2	312.2	490.0	294.4	306.0	302.5	305.3	304.3
CH_4	1.7	0.8	0.3	0.2	0.2	0.2	0.2
N_2O	12.8	13.6	3.2	2.9	2.4	2.0	1.7
HFCs	0.0	33.3	23.0	21.1	19.2	18.1	16.9
Medium- and Heavy-Duty							
Trucks	**230.3**	**404.1**	**413.9**	**417.9**	**431.4**	**442.1**	**444.4**
CO_2	229.3	399.4	406.0	409.7	422.8	433.2	435.2
CH_4	0.3	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.7	1.2	2.4	2.6	2.8	2.9	3.0
HFCs	0.0	3.4	5.5	5.5	5.7	5.9	6.1
Buses	**8.5**	**12.3**	**19.6**	**19.1**	**20.6**	**22.0**	**22.2**

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[10] In 2011 FHWA changed its methods for estimating VMT and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2008 Inventory and apply to the 2007 to 2019 time period. This resulted in large changes in VMT data by vehicle class, leading to a shift in emissions among on-road vehicle classes. This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this Inventory.

CO_2	8.4	11.8	18.9	18.4	19.9	21.2	21.4
CH_4	+	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
HFCs	0.0	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	**1.7**	**1.6**	**3.7**	**3.9**	**3.8**	**3.8**	**3.6**
CO_2	1.7	1.6	3.6	3.8	3.7	3.8	3.6
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
Commercial Aircraft[a]	**110.9**	**134.0**	**120.1**	**121.5**	**129.2**	**130.8**	**135.4**
CO_2	109.9	132.7	119.0	120.4	128.0	129.6	134.2
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	1.0	1.2	1.1	1.1	1.2	1.2	1.2
Other Aircraft[b]	**78.3**	**59.7**	**40.4**	**47.5**	**45.6**	**44.7**	**45.7**
CO_2	77.5	59.1	40.0	47.0	45.2	44.3	45.2
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.7	0.5	0.4	0.4	0.4	0.4	0.4
Ships and Boats[c]	**47.0**	**45.4**	**33.8**	**40.8**	**43.9**	**41.2**	**40.4**
CO_2	46.3	44.3	30.6	37.2	40.0	37.0	35.9
CH_4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N_2O	0.3	0.3	0.2	0.2	0.2	0.2	0.2
HFCs	0.0	0.5	2.6	2.9	3.3	3.6	3.9
Rail	**39.0**	**51.5**	**44.1**	**40.3**	**41.5**	**43.3**	**40.8**
CO_2	38.5	50.8	43.5	39.7	40.9	42.7	40.2
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.4	0.3	0.4	0.4	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	+	+	+	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.4**	**38.5**	**39.2**	**41.3**	**49.9**	**53.7**
CO_2	36.0	32.4	38.5	39.2	41.3	49.9	53.7
Total Transportation	**1,517.9**	**1,970.2**	**1,787.5**	**1,823.9**	**1,842.2**	**1,873.8**	**1,871.7**
International Bunker Fuels[f]	*54.8*	*44.7*	*31.6*	*35.0*	*34.6*	*32.5*	*26.4*
Ethanol CO_2[g]	*4.1*	*21.6*	*74.2*	*76.9*	*77.7*	*78.6*	*78.7*
Biodiesel CO_2[g]	*0.0*	*0.9*	*14.1*	*19.6*	*18.7*	*17.9*	*17.1*

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electric power plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

Commercial

The commercial end-use sector, with electricity-related emissions distributed, accounts for 15.6 percent of U.S. greenhouse gas emissions in 2019 and is heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use driven by a reduction in heating degree days and increases in energy efficiency.

Landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions decreasing slightly.

Residential

The residential end-use sector, with electricity-related emissions distributed, accounts for 14.9 percent of U.S. greenhouse gas emissions in 2019 and similarly, is heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households (EIA 2018).

Agriculture

The agriculture end-use sector accounts for 10.7 percent of U.S. greenhouse gas emissions in 2019 when electricity-related emissions are distributed, and includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2019, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors.

Box 2-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.1 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-21). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and associated fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.8 percent since 2005. Fossil fuel consumption has also decreased at a slower rate than

emissions since 2005, while total energy use, GDP, and national population continued to increase.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2015	2016	2017	2018	2019	Avg. Annual Change Since 1990[a]	Avg. Annual Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	104	101	101	104	102	0.1%	-0.8%
Energy Use[c]	100	119	116	116	116	120	119	0.6%	+%
GDP[d]	100	159	186	189	194	200	204	2.5%	1.8%
Population[e]	100	118	128	129	130	131	132	1.0%	0.8%

+ Does not exceed 0.05 percent.
[a] Average annual growth rate.
[b] GWP-weighted values.
[c] Energy-content-weighted values (EIA 2020b).
[d] GDP in chained 2009 dollars (BEA 2020).
[e] U.S. Census Bureau (2020).

Figure 2-21: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product
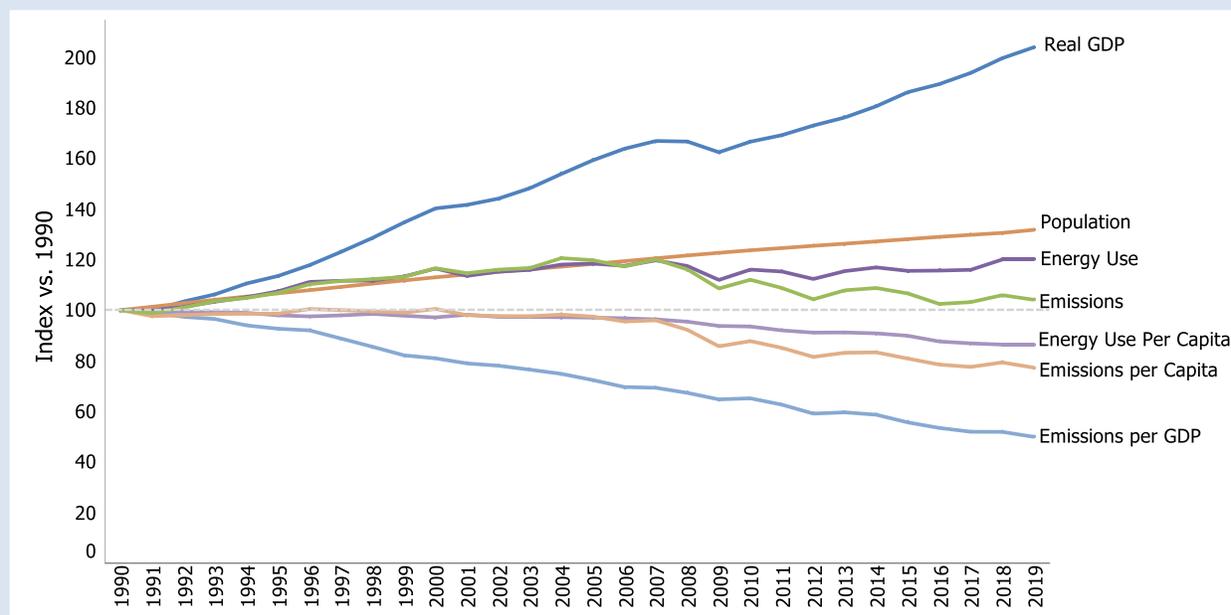
Source: BEA (2020), U.S. Census Bureau (2020), and emission estimates in this report.

2.3 Precursor Greenhouse Gas Emissions (CO, NO$_x$, NMVOCs, and SO$_2$)

The reporting requirements of the UNFCCC[11] request that information be provided on precursor greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO$_x$), non-CH$_4$ volatile organic compounds

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[11] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

(NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from N_2O. Non-methane volatile organic compounds—which include hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry. Sulfur-containing compounds emitted into the atmosphere tend to exert a negative radiative forcing (i.e., cooling) and therefore are discussed separately.

One important indirect climate change effect of NMVOCs and NO_x is their role as precursors for tropospheric ozone formation. They can also alter the atmospheric lifetimes of other greenhouse gases. Another example of indirect greenhouse gas formation into greenhouse gases is the interaction of CO with the hydroxyl radical—the major atmospheric sink for CH_4 emissions—to form CO_2. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy CH_4.

Since 1970, the United States has published estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2020b),[12] which are regulated under the Clean Air Act. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these indirect greenhouse gases. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2015	2016	2017	2018	2019
NO_x	**21,739**	**17,339**	**10,187**	**8,792**	**8,642**	**8,145**	**7,754**
Mobile Fossil Fuel Combustion	10,862	10,295	5,634	4,739	4,563	4,123	3,862
Stationary Fossil Fuel Combustion	10,023	5,858	3,084	2,856	2,728	2,711	2,581
Oil and Gas Activities	139	321	622	594	565	565	565
Industrial Processes and Product Use	592	572	408	402	397	397	397
Forest Fires	22	126	312	87	281	242	242
Waste Combustion	82	128	88	80	71	71	71
Grassland Fires	5	21	21	19	21	20	20
Agricultural Burning	13	15	14	14	14	14	14
Waste	+	2	2	1	1	1	1
CO	**130,969**	**71,781**	**51,525**	**39,287**	**45,314**	**42,355**	**41,524**
Mobile Fossil Fuel Combustion	119,360	58,615	32,635	28,789	28,124	26,590	25,749
Forest Fires	800	4,511	11,136	3,080	10,036	8,626	8,626
Stationary Fossil Fuel Combustion	5,000	4,648	3,688	3,690	3,692	3,692	3,692
Waste Combustion	978	1,403	1,576	1,375	1,175	1,175	1,175
Industrial Processes and Product Use	4,129	1,557	1,163	1,075	1,006	1,006	1,006
Oil and Gas Activities	302	318	622	607	592	592	592
Grassland Fires	84	358	356	324	345	331	341
Agricultural Burning	315	363	342	340	339	338	337
Waste	1	7	7	6	5	5	5
NMVOCs	**20,930**	**13,154**	**10,596**	**9,774**	**9,444**	**9,228**	**9,123**
Industrial Processes and Product Use	7,638	5,849	3,796	3,776	3,767	3,767	3,767
Mobile Fossil Fuel Combustion	10,932	5,724	3,458	2,873	2,758	2,543	2,437

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[12] NO_x and CO emission estimates from Field Burning of Agricultural Residues were estimated separately, and therefore not taken from EPA (2019b).

Oil and Gas Activities	554	510	2,656	2,459	2,262	2,262	2,262
Stationary Fossil Fuel Combustion	912	716	493	489	496	496	496
Waste Combustion	222	241	132	121	109	109	109
Waste	673	114	63	57	52	52	52
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
SO₂	**20,935**	**13,196**	**3,578**	**2,906**	**2,313**	**2,233**	**1,966**
Stationary Fossil Fuel Combustion	18,407	11,541	2,901	2,269	1,638	1,569	1,304
Industrial Processes and Product Use	1,307	831	482	466	509	509	509
Oil and Gas Activities	390	180	92	89	86	86	86
Mobile Fossil Fuel Combustion	793	619	78	57	58	47	45
Waste Combustion	38	25	26	24	22	22	22
Waste	+	1	1	1	1	1	1
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 kt.
NA (Not Available)
Source: (EPA 2020b) except for estimates from Forest Fires, Grassland Fires, and Field Burning of Agricultural Residues.

Box 2-3: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO₂) emitted into the atmosphere through natural and anthropogenic processes affects the earth's radiative budget through its photochemical transformation into sulfate aerosols that can:

(1) scatter radiation from the sun back to space, thereby reducing the radiation reaching the earth's surface;

(2) affect cloud formation; and

(3) affect atmospheric chemical composition (e.g., by providing surfaces for heterogeneous chemical reactions).

The indirect effect of sulfur-derived aerosols on radiative forcing can be considered in two parts. The first indirect effect is the aerosols' tendency to decrease water droplet size and increase water droplet concentration in the atmosphere. The second indirect effect is the tendency of the reduction in cloud droplet size to affect precipitation by increasing cloud lifetime and thickness. Although still highly uncertain, the radiative forcing estimates from both the first and the second indirect effect are believed to be negative, as is the combined radiative forcing of the two (IPCC 2013).

Sulfur dioxide is also a major contributor to the formation of regional haze, which can cause significant increases in acute and chronic respiratory diseases. Once SO₂ is emitted, it is chemically transformed in the atmosphere and returns to the earth as the primary source of acid rain. Because of these harmful effects, the United States has regulated SO₂ emissions in the Clean Air Act.

Electric power is the largest anthropogenic source of SO₂ emissions in the United States, accounting for 46.9 percent in 2019. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result of electric power generators switching from high-sulfur to low-sulfur coal and installing flue gas desulfurization equipment.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 82.2 percent of total greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2019.[1] This included 96.7, 40.6, and 9.5 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 77.5 percent of U.S. greenhouse gas emissions from all sources on a CO_2-equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (4.7 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1 and Figure 3-2). Globally, approximately 33,300 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2019, of which the United States accounted for approximately 15 percent.[2] Due to their relative importance over time (see Figure 3-2), fossil fuel combustion-related CO_2 emissions are considered separately and in more detail than other energy-related emissions (see Figure 3-3).

Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the third largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems.

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[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Energy related CO2 emissions, 1990-2019 – Charts* Available at: <https://www.iea.org/data-and-statistics/charts/energy-related-co2-emissions-1990-2019> (IEA 2020).

Figure 3-1: 2019 Energy Chapter Greenhouse Gas Sources
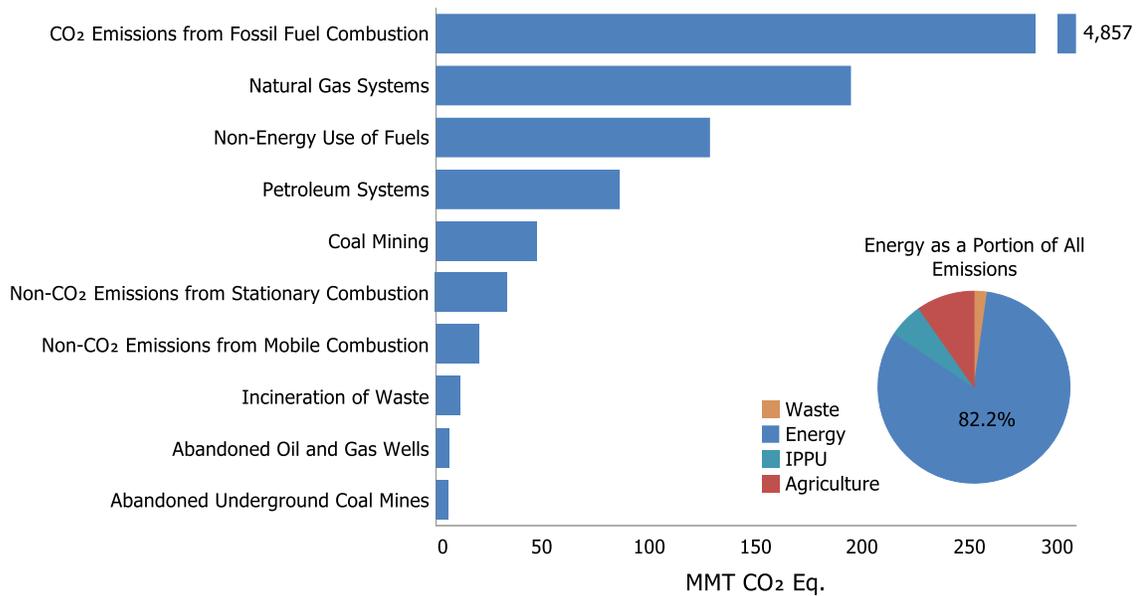
Figure 3-2: Trends in Energy Chapter Greenhouse Gas Sources
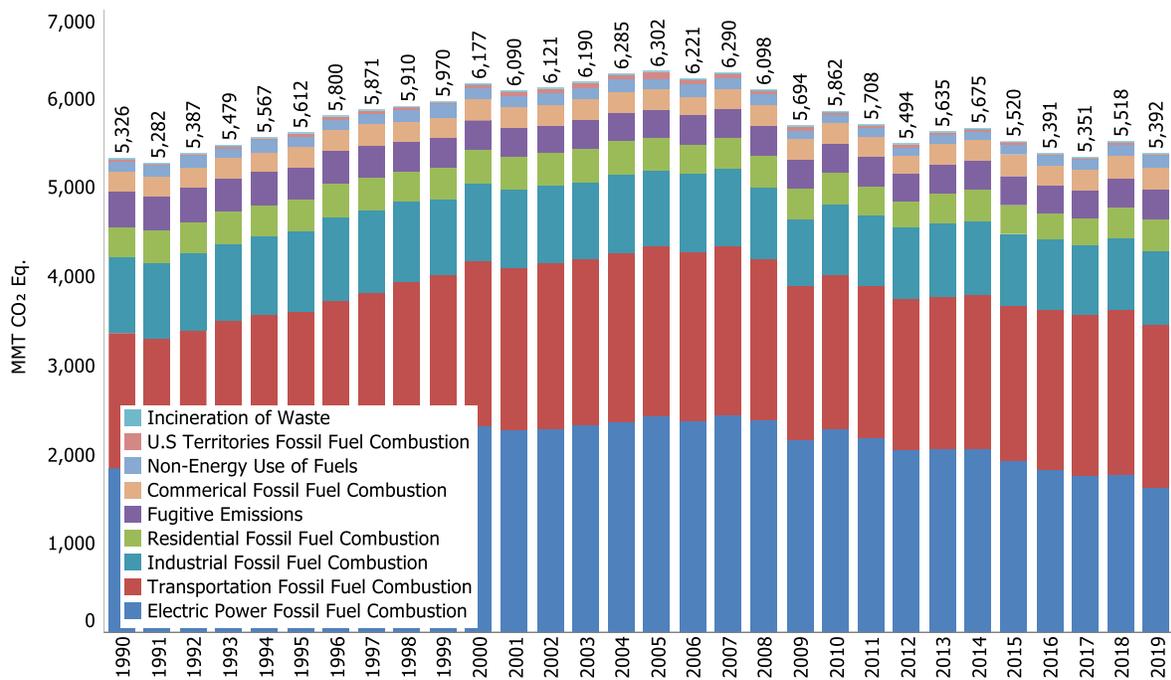
Figure 3-3: 2019 U.S. Fossil Carbon Flows
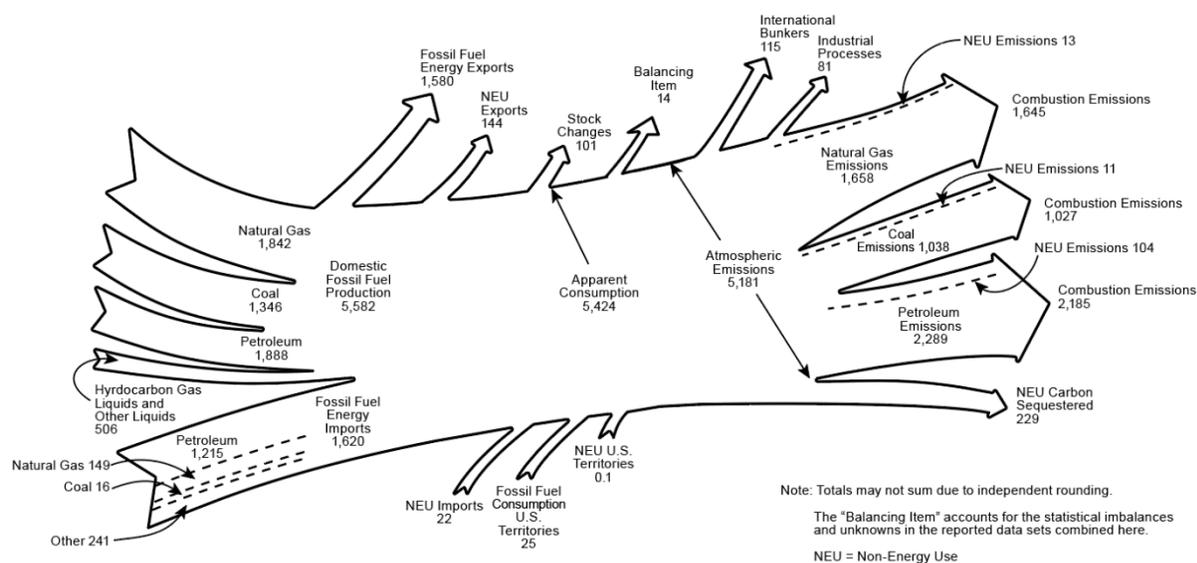
Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,392.3 MMT CO_2 Eq. in 2019,[3] an increase of 1.3 percent since 1990 and a decrease of 2.3 percent since 2018.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO_2	**4,894.1**	**5,932.6**	**5,189.8**	**5,074.8**	**5,035.7**	**5,203.7**	**5,081.4**
Fossil Fuel Combustion	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
Transportation	*1,469.1*	*1,858.6*	*1,719.2*	*1,759.9*	*1,782.4*	*1,816.6*	*1,817.2*
Electric Power	*1,820.0*	*2,400.1*	*1,900.6*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.0*
Industrial	*853.8*	*852.9*	*797.3*	*792.5*	*790.1*	*813.6*	*822.5*
Residential	*338.6*	*358.9*	*317.3*	*292.8*	*293.4*	*338.1*	*336.8*
Commercial	*228.3*	*227.1*	*244.6*	*231.6*	*232.0*	*245.7*	*249.7*
U.S. Territories	*21.7*	*55.9*	*29.2*	*26.0*	*24.6*	*24.6*	*24.6*
Non-Energy Use of Fuels	112.8	129.1	108.5	99.8	113.5	129.7	128.8
Petroleum Systems	9.7	12.1	32.4	21.8	25.0	37.1	47.3
Natural Gas Systems	32.0	25.2	29.1	30.1	31.2	33.9	37.2
Incineration of Waste	8.1	12.7	11.5	11.5	11.5	11.5	11.5
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*224.7*	*215.7*	*211.5*	*219.8*	*216.5*
International Bunker Fuels[b]	*103.5*	*113.2*	*110.9*	*116.6*	*120.1*	*122.1*	*116.1*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*78.9*	*81.2*	*82.1*	*81.9*	*82.6*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*14.1*	*19.6*	*18.7*	*17.9*	*17.1*
CH_4	**361.3**	**293.3**	**277.4**	**264.9**	**266.6**	**267.0**	**267.6**
Natural Gas Systems	186.9	164.2	149.8	147.3	148.7	152.5	157.6
Coal Mining	96.5	64.1	61.2	53.8	54.8	52.7	47.4
Petroleum Systems	48.9	39.5	41.5	39.2	39.3	37.3	39.1
Stationary Combustion	8.6	7.8	8.5	7.9	7.6	8.5	8.7
Abandoned Oil and Gas Wells	6.8	7.2	7.4	7.4	7.2	7.3	6.6

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[3] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

	1990	2005	2015	2016	2017	2018	2019
Abandoned Underground Coal Mines	7.2	6.6	6.4	6.7	6.4	6.2	5.9
Mobile Combustion	6.4	4.0	2.6	2.5	2.5	2.4	2.4
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N$_2$O	**70.3**	**76.3**	**52.6**	**51.2**	**48.6**	**47.4**	**43.2**
Stationary Combustion	25.1	34.4	30.5	30.0	28.4	28.2	24.9
Mobile Combustion	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*
Total	**5,325.6**	**6,302.3**	**5,519.8**	**5,390.9**	**5,351.0**	**5,518.1**	**5,392.3**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO$_2$ Eq.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Table 3-2: CO$_2$, CH$_4$, and N$_2$O Emissions from Energy (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO$_2$	**4,894,051**	**5,932,600**	**5,189,826**	**5,074,805**	**5,035,743**	**5,203,702**	**5,081,445**
Fossil Fuel Combustion	4,731,466	5,753,507	5,008,270	4,911,532	4,854,480	4,991,420	4,856,702
Non-Energy Use of Fuels	112,766	129,135	108,476	99,840	113,539	129,728	128,763
Petroleum Systems	9,709	12,059	32,412	21,847	24,979	37,115	47,269
Natural Gas Systems	32,042	25,179	29,127	30,054	31,200	33,885	37,234
Incineration of Waste	8,062	12,713	11,533	11,525	11,537	11,547	11,471
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Biomass-Wood[a]	*215,186*	*206,901*	*224,730*	*215,712*	*211,511*	*219,794*	*216,533*
International Bunker Fuels[b]	*103,463*	*113,232*	*110,908*	*116,611*	*120,121*	*122,112*	*116,064*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*78,934*	*81,250*	*82,088*	*81,917*	*82,578*
Biofuels-Biodiesel[a]	*0*	*856*	*14,077*	*19,648*	*18,705*	*17,936*	*17,080*
CH$_4$	**14,451**	**11,733**	**11,095**	**10,596**	**10,665**	**10,680**	**10,704**
Natural Gas Systems	7,478	6,567	5,994	5,894	5,949	6,101	6,305
Coal Mining	3,860	2,565	2,449	2,154	2,191	2,109	1,895
Petroleum Systems	1,955	1,579	1,659	1,568	1,574	1,492	1,563
Stationary Combustion	344	313	339	315	306	342	346
Abandoned Oil and Gas Wells	271	287	294	296	288	290	263
Abandoned Underground Coal Mines	288	264	256	268	257	247	237
Mobile Combustion	256	158	105	102	100	98	95
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*4*	*4*	*4*
N$_2$O	**236**	**256**	**177**	**172**	**163**	**159**	**145**
Stationary Combustion	84	115	102	101	95	95	84

Mobile Combustion	150		139		73	70	67	63	60
Incineration of Waste	2		1		1	1	1	1	1
Petroleum Systems	+		+		+	+	+	+	+
Natural Gas Systems	+		+		+	+	+	+	+
International Bunker Fuels[b]	*3*		*3*		*3*	*3*	*4*	*4*	*3*

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Emissions estimates reported in the Energy chapter from fossil fuel combustion and fugitive sources include those from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories including some non-CO_2 emissions from combustion. As part of continuous improvement efforts, EPA reviews this on an ongoing basis to ensure emission sources are included across all geographic areas including U.S. Territories if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this Inventory.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate. Key updates in this year's Inventory include updates to CO_2 emissions from Fossil Fuel Combustion (e.g., updates to CO_2 emission factors for gasoline and diesel fuels, updates to CH_4 and N_2O emission factors for newer non-road gasoline and diesel vehicles and changes to activity and carbon content coefficients), updates to carbon emissions from non-energy uses of fossil fuels (e.g., heat contents for hydrocarbon gas liquids) and updates to fugitive emission sources (e.g., CH_4 and CO_2 emissions from natural gas systems distribution and production). The combined impact of these recalculations averaged -10.5 MMT CO_2 Eq. (-0.2 percent) per year across the time series. For more information on specific methodological updates, please see the Recalculations section for each category in this chapter.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the Energy chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from energy-related activities.

Energy Data from EPA's Greenhouse Gas Reporting Program

EPA's Greenhouse Gas Reporting Program (GHGRP)[4] dataset and the data presented in this Inventory are complementary. The Inventory was used to guide the development of the GHGRP, particularly in terms of scope and coverage of both sources and gases. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of Energy sector categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see Box 3-3 of this chapter, and sections 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.6 Natural Gas Systems).[5] Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods. Under EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass.

In addition to using GHGRP data to estimate emissions (Section 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.7 Natural Gas Systems), EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 Emissions from Fossil Fuel Combustion, for use in reporting emissions in Common Reporting Format (CRF) tables (See Box 3-3). The industrial end-use sector activity data collected for the Inventory (EIA 2020) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this Inventory. See Annex 9 for more information on use of EPA's GHGRP in the Inventory.

3.1 Fossil Fuel Combustion (CRF Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the greenhouse gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. An overview of CH_4 and N_2O emissions from the combustion of fuels in stationary sources is then presented, followed by fossil fuel combustion emissions for all three gases by end-use sector: electric power, industrial, residential, commercial, U.S. Territories, and transportation.

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[4] On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[5] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2015	2016	2017	2018	2019
CO_2	4,731.5	5,753.5	5,008.3	4,911.5	4,854.5	4,991.4	4,856.7
CH_4	15.0	11.8	11.1	10.4	10.1	11.0	11.0
N_2O	69.8	75.9	52.3	50.8	48.3	47.1	42.9
Total	**4,816.3**	**5,841.2**	**5,071.6**	**4,972.8**	**4,912.9**	**5,049.5**	**4,910.6**

Note: Totals may not sum due to independent rounding.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2015	2016	2017	2018	2019
CO_2	4,731,466	5,753,507	5,008,270	4,911,532	4,854,480	4,991,420	4,856,702
CH_4	600	471	444	417	406	440	441
N_2O	234	255	175	171	162	158	144

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2019, CO_2 emissions from fossil fuel combustion decreased by 2.7 percent relative to the previous year (as shown in Table 3-6). The decrease in CO_2 emissions from fossil fuel consumption was a result of a 1 percent decrease in total energy use and reflects a continued shift from coal to less carbon intensive natural gas and renewables in the electric power sector. Carbon dioxide emissions from natural gas consumption increased by 53.4 MMT CO_2 Eq. in 2019, a 3.4 percent increase from 2018, while CO_2 emissions from coal consumption decreased by 185.3 MMT CO_2 Eq., a 15.2 percent decrease. The increase in natural gas consumption and emissions in 2019 is observed across all sectors and is primarily driven by a shift away from coal consumption in the Electric Power sector. In 2019, CO_2 emissions from fossil fuel combustion were 4,856.7 MMT CO_2 Eq., or 2.6 percent above emissions in 1990 (see Table 3-5).[6]

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2015	2016	2017	2018	2019
Coal	**1,719.8**	**2,113.7**	**1,428.5**	**1,310.7**	**1,270.2**	**1,211.6**	**1,027.1**
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	3.0	2.3	2.0	1.8	1.6
Industrial	157.8	117.8	70.0	63.2	58.7	54.4	49.5
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	1,351.4	1,242.0	1,207.1	1,152.9	973.5
U.S. Territories	0.5	3.0	4.1	3.2	2.5	2.5	2.5
Natural Gas	**1,000.0**	**1,167.0**	**1,454.9**	**1,461.3**	**1,434.6**	**1,591.2**	**1,644.6**
Residential	237.8	262.2	252.7	238.4	241.5	273.8	275.3
Commercial	142.0	162.9	175.4	170.5	173.2	192.5	192.8
Industrial	408.8	388.6	459.1	463.9	469.5	494.0	503.3
Transportation	36.0	33.1	39.4	40.1	42.3	50.9	54.8
Electric Power	175.4	318.9	525.2	545.0	505.6	577.4	616.0

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[6] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

U.S. Territories	NO	1.3	3.0	3.4	2.5	2.5	2.5
Petroleum	**2,011.2**	**2,472.3**	**2,124.5**	**2,139.2**	**2,149.2**	**2,188.2**	**2,184.6**
Residential	97.8	95.9	64.6	54.4	51.9	64.2	61.5
Commercial	74.3	54.9	66.2	58.7	56.8	51.4	55.3
Industrial	287.2	346.4	268.2	265.4	261.9	265.2	269.7
Transportation	1,433.1	1,825.6	1,679.8	1,719.8	1,740.2	1,765.6	1,762.5
Electric Power	97.5	98.0	23.7	21.5	18.9	22.2	16.2
U.S. Territories	21.2	51.6	22.1	19.4	19.5	19.5	19.5
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Total	**4,731.5**	**5,753.5**	**5,008.3**	**4,911.5**	**4,854.5**	**4,991.4**	**4,856.7**

Note: Totals may not sum due to independent rounding.

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, HVAC systems, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Carbon dioxide emissions also depend on the source of energy and its carbon (C) intensity. The amount of C in fuels varies significantly by fuel type. For example, coal contains the highest amount of C per unit of useful energy. Petroleum has roughly 75 percent of the C per unit of energy as coal, and natural gas has only about 55 percent.[7] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

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[7] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States. See Annex 2.2 for more details on fuel carbon contents.

Table 3-6: Annual Change in CO₂ Emissions and Total 2019 CO₂ Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO₂ Eq. and Percent)

Sector	Fuel Type	2015 to 2016		2016 to 2017		2017 to 2018		2018 to 2019		Total 2019
Electric Power	Coal	-109.4	-8.1%	-34.9	-2.8%	-54.2	-4.5%	-179.3	-15.6%	973.5
Electric Power	Natural Gas	19.8	3.8%	-39.4	-7.2%	71.8	14.2%	38.5	6.7%	616.0
Electric Power	Petroleum	-2.2	-9.4%	-2.5	-11.8%	3.3	17.4%	-6.1	-27.3%	16.2
Transportation	Petroleum	40.0	2.4%	20.4	1.2%	25.5	1.5%	-3.2	-0.2%	1,762.5
Residential	Natural Gas	-14.3	-5.7%	3.1	1.3%	32.3	13.4%	1.5	0.5%	275.3
Commercial	Natural Gas	-4.9	-2.8%	2.6	1.6%	19.3	11.2%	0.3	0.1%	192.8
Industrial	Natural Gas	4.8	1.0%	5.6	1.2%	24.5	5.2%	9.3	1.9%	503.3
Electric Power	**All Fuels[a]**	**-91.8**	**-4.8%**	**-76.8**	**-4.2%**	**20.9**	**1.2%**	**-146.9**	**-8.4%**	**1,606.0**
Transportation	**All Fuels[a]**	**40.6**	**2.4%**	**22.6**	**1.3%**	**34.1**	**1.9%**	**0.6**	**+%**	**1,817.2**
Residential	**All Fuels[a]**	**-24.5**	**-7.7%**	**0.6**	**0.2%**	**44.7**	**15.2%**	**-1.3**	**-0.4%**	**336.8**
Commercial	**All Fuels[a]**	**-13.0**	**-5.3%**	**0.4**	**0.2%**	**13.7**	**5.9%**	**4.0**	**1.6%**	**249.7**
Industrial	**All Fuels[a]**	**-4.8**	**-0.6%**	**-2.4**	**-0.3%**	**23.5**	**3.0%**	**8.9**	**1.1%**	**822.5**
All Sectors[a]	**All Fuels[a]**	**-96.7**	**-1.9%**	**-57.1**	**-1.2%**	**136.9**	**2.8%**	**-134.7**	**-2.7%**	**4,856.7**

[a] Includes sector and fuel combinations not shown in this table.

+ Does not exceed 0.05 percent.

As shown in Table 3-6, recent trends in CO₂ emissions from fossil fuel combustion show a 1.9 percent decrease from 2015 to 2016, a 1.2 percent decrease from 2016 to 2017, a 2.8 percent increase from 2017 to 2018, and a 2.7 percent decrease from 2018 to 2019. These changes contributed to an overall 3.0 percent decrease in CO₂ emissions from fossil fuel combustion from 2015 to 2019.

Trends in CO₂ emissions from fossil fuel combustion over the past five years are largely driven by the electric power sector, which until recently has accounted for the largest portion of these emissions. The types of fuels consumed to produce electricity have changed in recent years. Electric power sector consumption of natural gas primarily increased due to increased production capacity as natural gas-fired plants replaced coal-fired plants and increased electricity demand related to heating and cooling needs (EIA 2018; EIA 2020f). Total electric power generation increased by 0.01 percent from 2015 to 2016, decreased by 1.0 percent from 2016 to 2017, increased by 3.6 percent from 2017 to 2018 and decreased by 1.4 percent from 2018 to 2019. Carbon dioxide emissions decreased from 2018 to 2019 by 8.4 percent due to increasing electric power generation from natural gas and decreasing generation from petroleum and coal. Carbon dioxide emissions from coal consumption for electric power generation decreased by 28.0 percent since 2015, which can be largely attributed to a shift to the use of less-CO₂-intensive natural gas to generate electricity and a rapid increase in renewable energy capacity additions in the electric power sector in recent years.

The trends in CO₂ emissions from fossil fuel combustion over the past five years also follow changes in heating degree days (see Box 3-2). Emissions from natural gas consumption in the residential and commercial sectors increased by 8.2 percent and 9.0 percent from 2015 to 2019, respectively. This trend can be largely attributed to a 5.3 percent increase in heating degree days from 2015 to 2019, which led to an increased demand for heating fuel and electricity for heat in these sectors. Industrial consumption of natural gas is dependent on market effects of supply and demand in addition to weather-related heating needs.

Petroleum use in the transportation sector is another major driver of emissions, representing the largest source of CO₂ emissions from fossil fuel combustion in 2019. Emissions from petroleum consumption for transportation have increased by 4.9 percent since 2015 and are primarily attributed to a 5.4 percent increase in vehicle miles traveled (VMT) over the same time period. Beginning with 2017, the transportation sector is the largest source of national CO₂ emissions – whereas in prior years, electric power was the largest source sector.

In the United States, 80 percent of the energy used in 2019 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-4 and Figure 3-5). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 37 percent of total U.S. energy used in 2019. Natural gas and coal followed in order of energy demand importance, accounting for approximately 32 percent and 11 percent

of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the majority of coal was used in the electric power sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-6) (EIA 2020c). The remaining portion of energy used in 2019 was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (11 percent), primarily hydroelectric power, wind energy, and biofuels (EIA 2020c).[8]

Figure 3-4: 2019 U.S. Energy Use by Energy Source

- Nuclear Electric Power 8.4%
- Renewable Energy 11.3%
- Petroleum 36.8%
- Coal 11.3%
- Natural Gas 32.1%
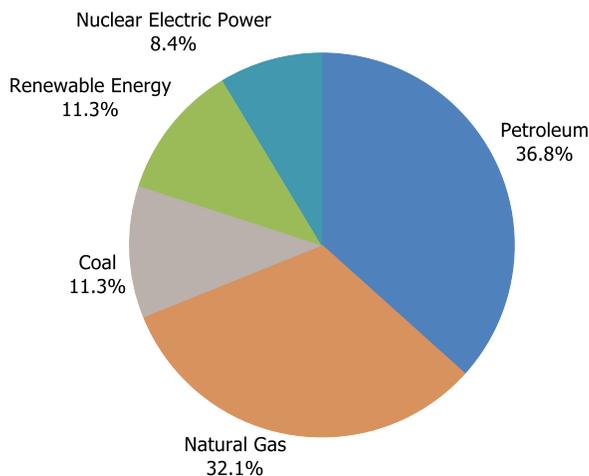
Figure 3-5: Annual U.S. Energy Use

Sum of Energy Consumption (QBtu) vs years 1990–2019

- Total Energy
- Fossil Fuels
- Renewable & Nuclear

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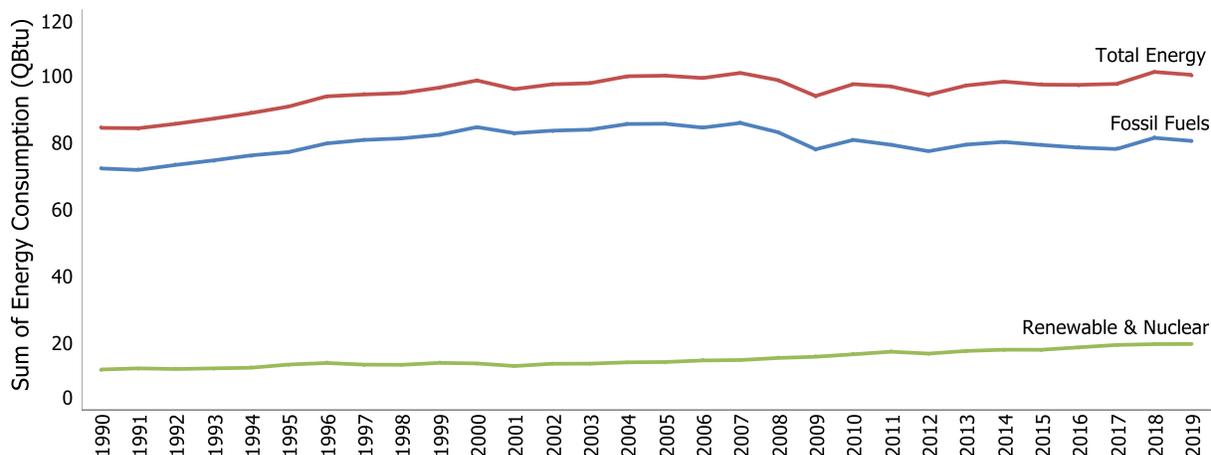
[8] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biofuels, solar energy, and wind energy.

Figure 3-6: 2019 CO$_2$ Emissions from Fossil Fuel Combustion by Sector and Fuel Type
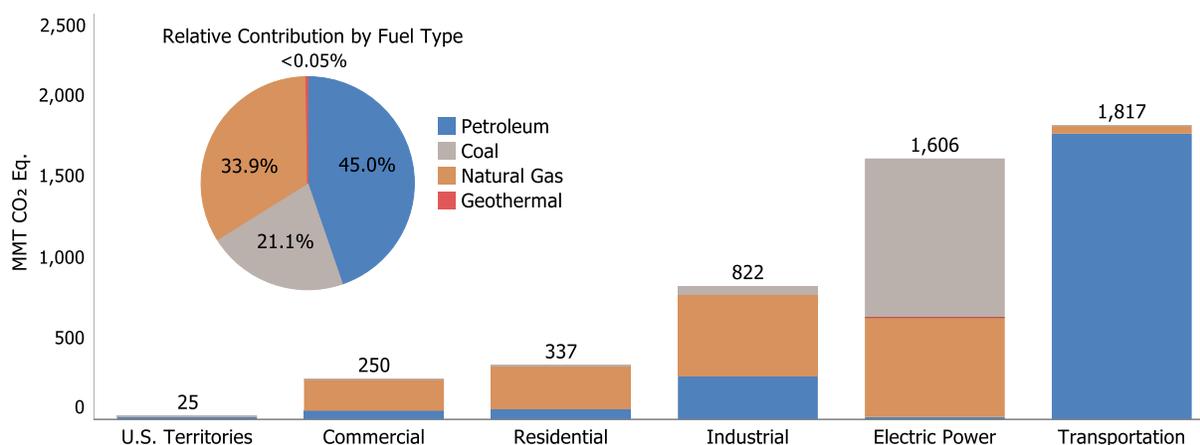
Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO$_2$ and smaller amounts of other gases, including CH$_4$, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[9] These other C-containing non-CO$_2$ gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO$_2$ in the atmosphere. Therefore, as per IPCC guidelines it is assumed all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO$_2$.

Box 3-2: Weather and Non-Fossil Energy Effects on CO$_2$ Emissions from Fossil Fuel Combustion Trends

The United States in 2019 experienced a slightly colder winter overall compared to 2018, as heating degree days increased 0.6 percent. Colder winter conditions compared to 2018 impacted the amount of energy required for heating. However, in 2019 heating degree days in the United States were still 5.2 percent below normal (see Figure 3-7). Cooling degree days decreased by 5.4 percent compared to 2018, which reduced demand for air conditioning in the residential and commercial sector. Cooler summer conditions compared to 2018 impacted the amount of energy required for cooling, however, 2019 cooling degree days in the United States were still 22.2 percent above normal (see Figure 3-8) (EIA 2020c).[10] The combination of slightly colder winter and cooler summer conditions led to overall residential and commercial energy consumption decreases of 0.4 and 1.6 percent, respectively relative to 2018.

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[9] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO$_2$ gas emissions from fossil fuel combustion.

[10] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1981 through 2010. The variation in these normals during this time period was ±15 percent and ±23 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-7: Annual Deviations from Normal Heating Degree Days for the United States (1950–2019, Index Normal = 100)

Normal
(4,538 Heating Degree Days)

99% Confidence

Note: Climatological normal data are highlighted in dark red. Statistical confidence interval for "normal" climatology period of 1981 through 2010.

Percent Deviation from Normal
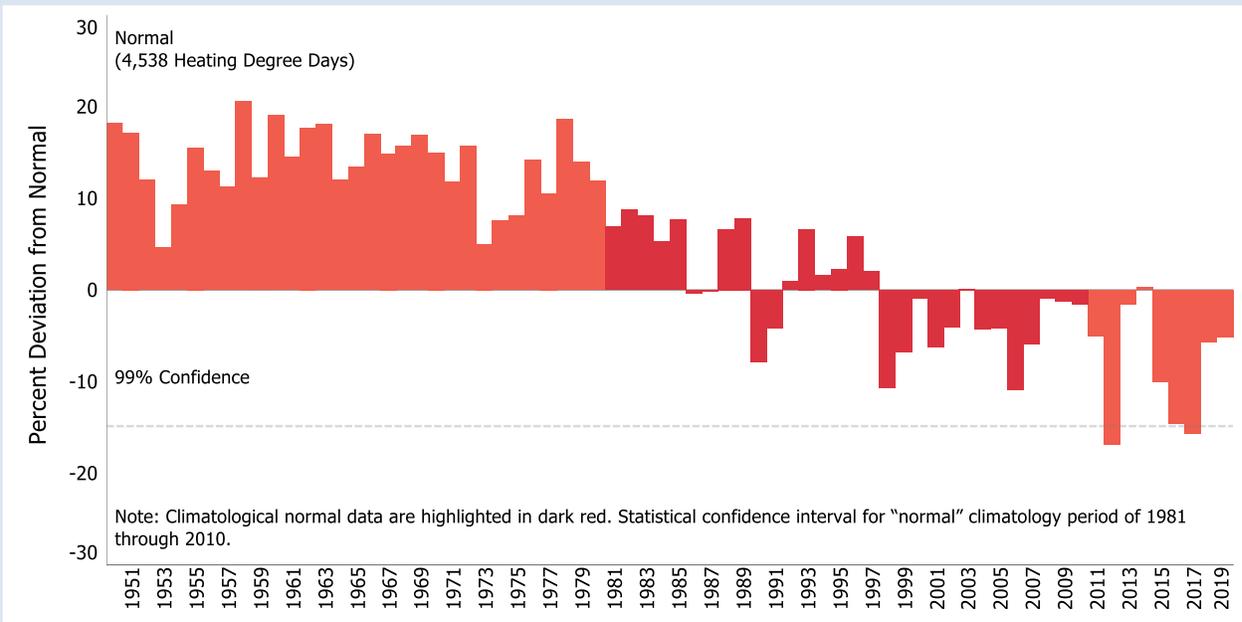
Figure 3-8: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2019, Index Normal = 100)

Normal
(1,228 cooling degree days)

99% Confidence

Note: Climatological normal data are highlighted dark blue. Statistical confidence interval for "normal" climatology period of 1981 through 2010.

Percent Deviation from Normal
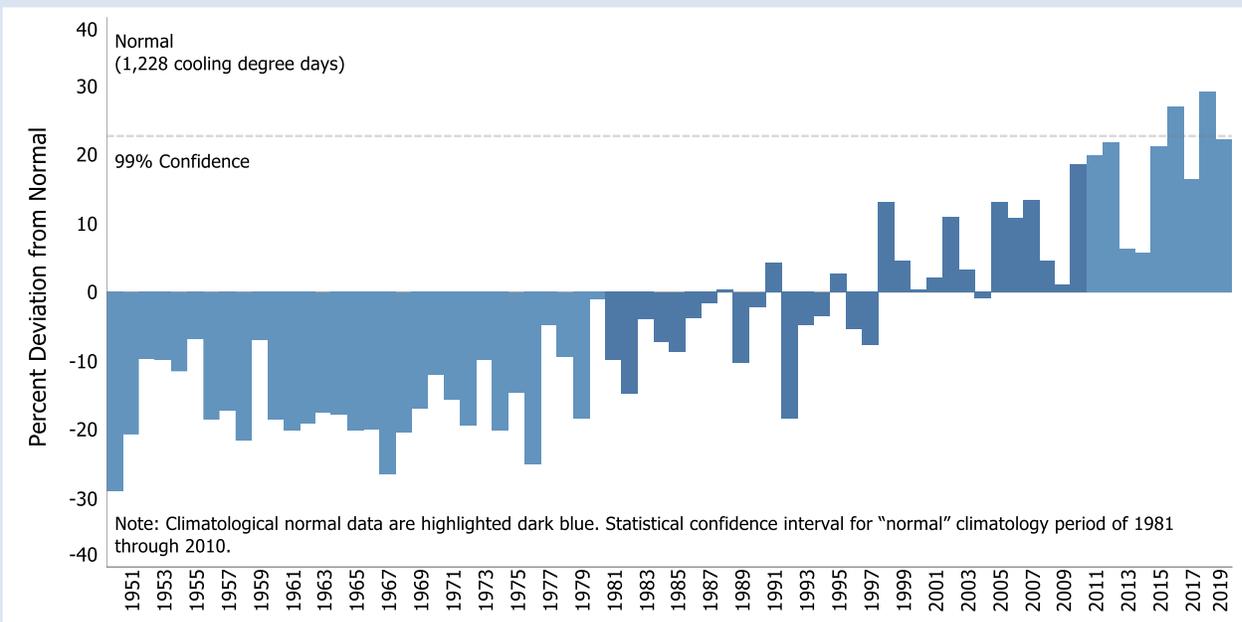
The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[11] of nuclear power plants in 2019 remained high at 94 percent. In 2019, nuclear power represented 20 percent of total electricity generation. Since 1990, the wind and solar power sectors have shown strong growth (between an observed minimum of 89 percent annual electricity generation growth to a maximum of 162 percent annual electricity generation growth) and have become relatively important electricity sources. Between 1990 and 2019, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 9 percent in 2019 of total electricity generation, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-7 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see Methodology section of CO_2 from Fossil Fuel Combustion). In addition to the CO_2 emitted from fossil fuel combustion, CH_4 and N_2O are emitted as well. Table 3-8 and Table 3-9 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emissions are estimated by applying a "bottom-up" methodology that utilizes facility-specific technology and fuel use data reported to EPA's Acid Rain Program (EPA 2020a) (see Methodology section for CH_4 and N_2O from Stationary Combustion).

Table 3-7: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2015	2016	2017	2018	2019
Electric Power	**1,820.0**	**2,400.1**	**1,900.6**	**1,808.9**	**1,732.0**	**1,752.9**	**1,606.0**
Coal	1,546.5	1,982.8	1,351.4	1,242.0	1,207.1	1,152.9	973.5
Natural Gas	175.4	318.9	525.2	545.0	505.6	577.4	616.0
Fuel Oil	97.5	98.0	23.7	21.5	18.9	22.2	16.2
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Industrial	**853.8**	**852.9**	**797.3**	**792.5**	**790.1**	**813.6**	**822.5**
Coal	157.8	117.8	70.0	63.2	58.7	54.4	49.5
Natural Gas	408.8	388.6	459.1	463.9	469.5	494.0	503.3
Fuel Oil	287.2	346.4	268.2	265.4	261.9	265.2	269.7
Commercial	**228.3**	**227.1**	**244.6**	**231.6**	**232.0**	**245.7**	**249.7**
Coal	12.0	9.3	3.0	2.3	2.0	1.8	1.6
Natural Gas	142.0	162.9	175.4	170.5	173.2	192.5	192.8
Fuel Oil	74.3	54.9	66.2	58.7	56.8	51.4	55.3
Residential	**338.6**	**358.9**	**317.3**	**292.8**	**293.4**	**338.1**	**336.8**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	237.8	262.2	252.7	238.4	241.5	273.8	275.3
Fuel Oil	97.8	95.9	64.6	54.4	51.9	64.2	61.5
U.S. Territories	**21.7**	**55.9**	**29.2**	**26.0**	**24.6**	**24.6**	**24.6**
Coal	0.5	3.0	4.1	3.2	2.5	2.5	2.5
Natural Gas	NO	1.3	3.0	3.4	2.5	2.5	2.5
Fuel Oil	21.2	51.6	22.1	19.4	19.5	19.5	19.5
Total	**3,262.4**	**3,894.9**	**3,289.0**	**3,151.7**	**3,072.0**	**3,174.9**	**3,039.5**

Note: Totals may not sum due to independent rounding.
NO (Not Occurring)

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[11] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)." Data for both the generation and net summer capacity are from EIA (2019).

Table 3-8: CH₄ Emissions from Stationary Combustion (MMT CO₂ Eq.)

Sector/Fuel Type	1990	2005	2015	2016	2017	2018	2019
Electric Power	**0.4**	**0.9**	**1.2**	**1.2**	**1.1**	**1.2**	**1.3**
Coal	0.3	0.4	0.3	0.2	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	0.9	0.9	0.9	1.0	1.1
Wood	+	+	+	+	+	+	+
Industrial	**1.8**	**1.7**	**1.6**	**1.6**	**1.5**	**1.5**	**1.5**
Coal	0.4	0.3	0.2	0.2	0.2	0.1	0.1
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.0	1.0	1.1	1.0	1.0	1.0	1.0
Commercial	**1.1**	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Natural gas	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Wood	0.5	0.5	0.6	0.6	0.6	0.6	0.6
Residential	**5.2**	**4.1**	**4.5**	**3.9**	**3.8**	**4.5**	**4.6**
Coal	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Fuel Oil	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Natural Gas	0.5	0.6	0.6	0.5	0.5	0.6	0.6
Wood	4.1	3.1	3.7	3.1	3.0	3.7	3.8
U.S. Territories	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NO	NO	NO	NO	NO	NO	NO
Total	**8.6**	**7.8**	**8.5**	**7.9**	**7.6**	**8.5**	**8.7**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO₂ Eq.
NO (Not Occurring)

Table 3-9: N₂O Emissions from Stationary Combustion (MMT CO₂ Eq.)

Sector/Fuel Type	1990	2005	2015	2016	2017	2018	2019
Electric Power	**20.5**	**30.1**	**26.5**	**26.2**	**24.8**	**24.4**	**21.1**
Coal	20.1	28.0	22.8	22.4	21.2	20.3	16.7
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.9	3.7	3.8	3.6	4.1	4.4
Wood	+	+	+	+	+	+	+
Industrial	**3.1**	**2.9**	**2.6**	**2.6**	**2.5**	**2.5**	**2.5**
Coal	0.7	0.6	0.3	0.3	0.3	0.3	0.2
Fuel Oil	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Natural Gas	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Wood	1.6	1.6	1.7	1.7	1.6	1.6	1.6
Commercial	**0.4**	**0.3**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.2	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**1.0**	**0.9**	**0.9**	**0.8**	**0.7**	**0.9**	**0.9**
Coal	+	+	0.0	0.0	0.0	0.0	0.0
Fuel Oil	0.2	0.2	0.2	0.1	0.1	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Wood	0.7	0.5	0.6	0.5	0.5	0.6	0.6
U.S. Territories	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NO	NO	NO	NO	NO	NO	NO
Total	**25.1**	**34.4**	**30.5**	**30.0**	**28.4**	**28.2**	**24.9**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

Fossil Fuel Combustion Emissions by Sector

Table 3-10 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector, including transportation, electric power, industrial, residential, commercial, and U.S. territories.

Table 3-10: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2015	2016	2017	2018	2019
Transportation	**1,520.2**	**1,904.2**	**1,743.6**	**1,783.2**	**1,804.8**	**1,837.8**	**1,837.5**
CO_2	1,469.1	1,858.6	1,719.2	1,759.9	1,782.4	1,816.6	1,817.2
CH_4	6.4	4.0	2.6	2.5	2.5	2.4	2.4
N_2O	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Electric Power	**1,840.9**	**2,431.0**	**1,928.3**	**1,836.2**	**1,757.9**	**1,778.5**	**1,628.4**
CO_2	1,820.0	2,400.1	1,900.6	1,808.9	1,732.0	1,752.9	1,606.0
CH_4	0.4	0.9	1.2	1.2	1.1	1.2	1.3
N_2O	20.5	30.1	26.5	26.2	24.8	24.4	21.1
Industrial	**858.7**	**857.6**	**801.5**	**796.7**	**794.2**	**817.6**	**826.5**
CO_2	853.8	852.9	797.3	792.5	790.1	813.6	822.5
CH_4	1.8	1.7	1.6	1.6	1.5	1.5	1.5
N_2O	3.1	2.9	2.6	2.6	2.5	2.5	2.5
Residential	**344.9**	**363.8**	**322.6**	**297.4**	**297.9**	**343.5**	**342.3**
CO_2	338.6	358.9	317.3	292.8	293.4	338.1	336.8
CH_4	5.2	4.1	4.5	3.9	3.8	4.5	4.6
N_2O	1.0	0.9	0.9	0.8	0.7	0.9	0.9
Commercial	**229.8**	**228.6**	**246.2**	**233.1**	**233.5**	**247.3**	**251.3**
CO_2	228.3	227.1	244.6	231.6	232.0	245.7	249.7
CH_4	1.1	1.1	1.2	1.2	1.2	1.2	1.2
N_2O	0.4	0.3	0.4	0.3	0.3	0.3	0.3
U.S. Territories[a]	**21.8**	**56.1**	**29.3**	**26.1**	**24.6**	**24.7**	**24.7**
Total	**4,816.3**	**5,841.2**	**5,071.6**	**4,972.8**	**4,912.9**	**5,049.5**	**4,910.6**

Note: Totals may not sum due to independent rounding.

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.

Other than greenhouse gases CO_2, CH_4, and N_2O, gases emitted from stationary combustion include the greenhouse gas precursors nitrogen oxides (NO_x), CO, and NMVOCs.[12] Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics, size and vintage of combustion device, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes

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[12] Sulfur dioxide (SO_2) emissions from stationary combustion are addressed in Annex 6.3.

and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed. Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion also produces emissions of CH_4, N_2O, and greenhouse gas precursors including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in vehicle idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-11 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[13] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[14] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-11.

Table 3-11: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2015	2016	2017	2018	2019
Transportation	**1,523.3**	**1,908.9**	**1,747.9**	**1,787.4**	**1,809.1**	**1,842.5**	**1,842.3**
CO_2	1,472.2	1,863.4	1,723.5	1,764.1	1,786.8	1,821.2	1,821.9
CH_4	6.4	4.0	2.6	2.5	2.5	2.4	2.4
N_2O	44.7	41.6	21.7	20.8	19.8	18.8	18.0
Industrial	**1,553.0**	**1,603.4**	**1,359.1**	**1,322.1**	**1,306.1**	**1,326.3**	**1,298.3**
CO_2	1,540.2	1,589.2	1,346.8	1,310.1	1,294.5	1,314.9	1,287.8
CH_4	2.0	2.0	1.9	1.9	1.9	1.9	1.9
N_2O	10.8	12.2	10.3	10.1	9.8	9.5	8.6
Residential	**944.4**	**1,230.9**	**1,016.4**	**960.8**	**924.2**	**995.0**	**933.9**
CO_2	931.3	1,214.9	1,001.1	946.2	910.5	980.2	920.3
CH_4	5.4	4.4	4.9	4.3	4.2	5.0	5.1
N_2O	7.7	11.6	10.4	10.3	9.6	9.9	8.6
Commercial	**773.7**	**1,041.9**	**918.9**	**876.3**	**848.8**	**861.0**	**811.4**
CO_2	766.0	1,030.1	907.6	865.2	838.2	850.6	802.1
CH_4	1.2	1.4	1.6	1.6	1.6	1.6	1.7
N_2O	6.5	10.4	9.6	9.5	9.0	8.8	7.6
U.S. Territories[a]	**21.8**	**56.1**	**29.3**	**26.1**	**24.6**	**24.7**	**24.7**
Total	**4,816.3**	**5,841.2**	**5,071.6**	**4,972.8**	**4,912.9**	**5,049.5**	**4,910.6**

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

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[13] Separate calculations are performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions is discussed in the Mobile Combustion section.

[14] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Electric Power Sector

The process of generating electricity is the largest stationary source of CO_2 emissions in the United States, representing 30.6 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 1.3 percent, respectively. Electric power also accounted for 33.1 percent of CO_2 emissions from fossil fuel combustion in 2019. Methane and N_2O from electric power represented 11.4 and 49.3 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2019, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Electric generation is reported as occurring in other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[15]

Total greenhouse gas emissions from the electric power sector have decreased by 11.5 percent since 1990. From 1990 to 2007, electric power sector emissions increased by 32 percent, driven by a significant increase in electricity demand (37 percent) while the carbon intensity of electricity generated showed a minor increase (0.3 percent). From 2008 to 2019, as electricity demand increased by only 2 percent, electric power sector emissions decreased by 13 percent, driven by a significant drop (26 percent) in the carbon intensity of electricity generated. Overall, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, decreased by 16 percent from 1990 to 2019 with additional trends detailed in Box 3-4. This decoupling of electric power generation and the resulting CO_2 emissions is shown in Figure 3-9. This recent decarbonization of the electric power sector is a result of several key drivers.

Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 24 percent in 2019.[16] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the 30-year period to represent 37 percent of electric power sector generation in 2019 (see Table 3-12). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation. Natural gas and coal used in the U.S. in 2019 had an average carbon content of 14.43 MMT C/QBtu and 26.08 MMT C/QBtu respectively.

Table 3-12: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990		2005		2015	2016	2017	2018	2019
Coal	54.1%		51.1%		34.2%	31.4%	30.9%	28.4%	24.2%
Natural Gas	10.7%		17.5%		31.6%	32.7%	30.9%	34.0%	37.3%
Nuclear	19.9%		20.0%		20.4%	20.6%	20.8%	20.1%	20.4%
Renewables	11.3%		8.3%		13.0%	14.7%	16.8%	16.8%	17.6%
Petroleum	4.1%		3.0%		0.7%	0.6%	0.5%	0.6%	0.4%
Other Gasesª	+%		0.1%		0.1%	0.1%	0.1%	0.1%	0.1%

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[15] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities typically generate electricity for sale on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

[16] Values represent electricity *net* generation from the electric power sector (EIA 2020c).

Net Electricity Generation (Billion kWh)[b]	*2,905*		*3,902*		*3,917*	*3,917*	*3,877*	*4,017*	*3,962*

+ Does not exceed 0.05 percent.

[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2019, CO_2 emissions from the electric power sector decreased by 8.4 percent relative to 2018. This decrease in CO_2 emissions was primarily driven by a decrease in coal and petroleum consumed to produce electricity in the electric power sector as well as a decrease in electricity demand (1.2 percent reduction in retail sales). Consumption of coal for electric power decreased by 15.5 percent while consumption of natural gas increased 6.7 percent from 2018 to 2019. There has also been a rapid increase in renewable energy electricity generation in the electric power sector in recent years. Electricity generation from renewable sources increased by 3 percent from 2018 to 2019 (see Table 3-12). The decrease in coal-powered electricity generation and increase in natural gas and renewable energy electricity generation contributed to a decoupling of emissions trends from electric power generation trends over the recent time series (see Figure 3-9).

Decreases in natural gas prices and the associated increase in natural gas generation, particularly between 2005 and 2019, was one of the main drivers of the recent fuel switching and decrease in electric power sector carbon intensity. During this time period, the cost of natural gas (in $/MMBtu) decreased by 56 percent while the cost of coal (in $/MMBtu) increased by 74 percent (EIA 2020c). Also, between 1990 and 2019, renewable energy generation (in kWh) from wind and solar energy increased from 0.1 percent of total generation in 1990 to 9 percent in 2019, which also helped drive the decrease in electric power sector carbon intensity. This decrease in carbon intensity occurred even as total electricity retail sales increased 41 percent, from 2,713 billion kWh in 1990 to 3,811 billion kWh in 2019.

Figure 3-9: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions
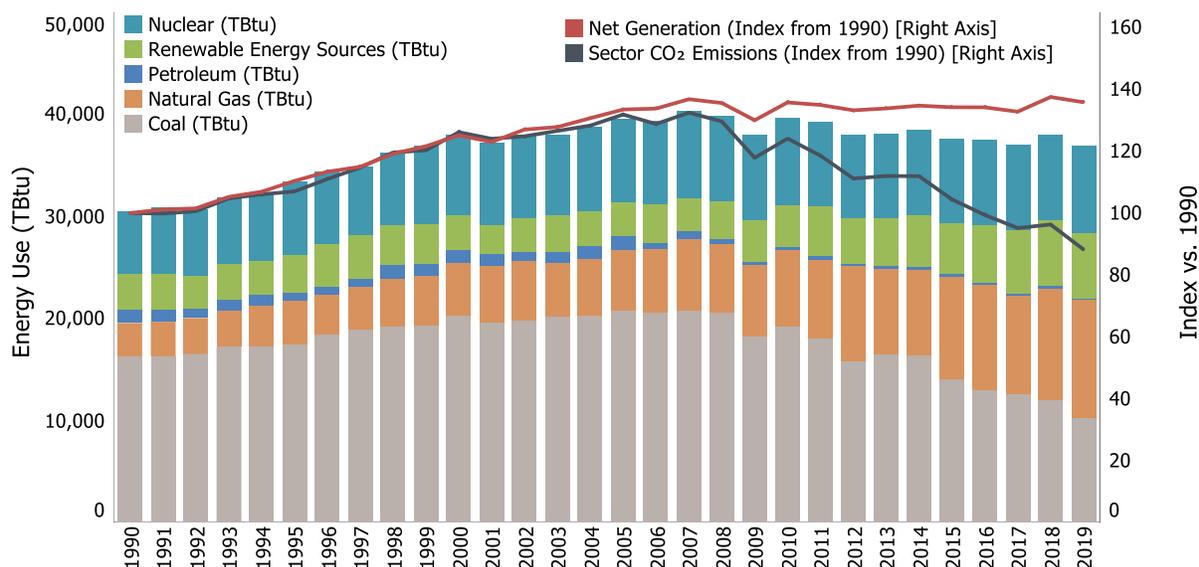
Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-10). Note that transportation is an end-use sector as well but is not shown in Figure 3-10 due to the sector's relatively low percentage of electricity use. Table 3-13 provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-10: Electric Power Retail Sales by End-Use Sector
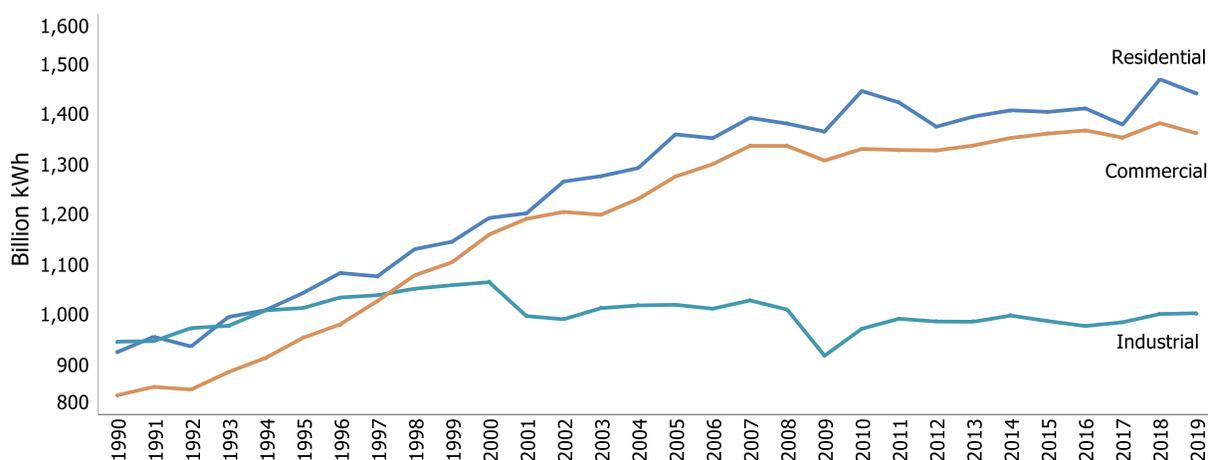
In 2019, electricity sales to the residential and commercial end-use sectors, as presented in Figure 3-10, decreased by 2.0 percent and 1.5 percent relative to 2018, respectively. Electricity sales to the industrial sector in 2019 increased approximately 0.2 percent relative to 2018. The sections below describe end-use sector energy use in more detail. Overall, in 2019, the amount of electricity retail sales (in kWh) decreased by 1.2 percent relative to 2018.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O emissions accounted for 17, 14, and 6 percent of CO_2, CH_4, and N_2O emissions from fossil fuel combustion, respectively in 2019. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Paper, Primary Metals, Food, and Nonmetallic Mineral Products—represent the majority of the energy use (EIA 2020c; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[17] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2018 to 2019, total industrial production and manufacturing output increased by 0.2 percent (FRB 2019). Over this period, output increased across production indices for Food, and Nonmetallic Mineral Products, and decreased slightly for Paper, Petroleum Refineries, Chemicals, and Primary Metals (see Figure 3-11). From 2018 to 2019, total energy use in the industrial sector increased by 1.5 percent. Due to the relative increases and decreases of individual indices there was an increase in natural gas and a decrease in electricity used by the sector (see Figure 3-12). In 2019, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,298.3 MMT CO_2 Eq., a 2.1 percent decrease from 2018 emissions.

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[17] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations. For example, from 2018 to 2019, the underlying EIA data showed decreased consumption of coal, and increase of natural gas in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; food processing, beverages and tobacco; minerals manufacturing; and agriculture-forest-fisheries.[18]

Figure 3-11: Industrial Production Indices (Index 2012=100)
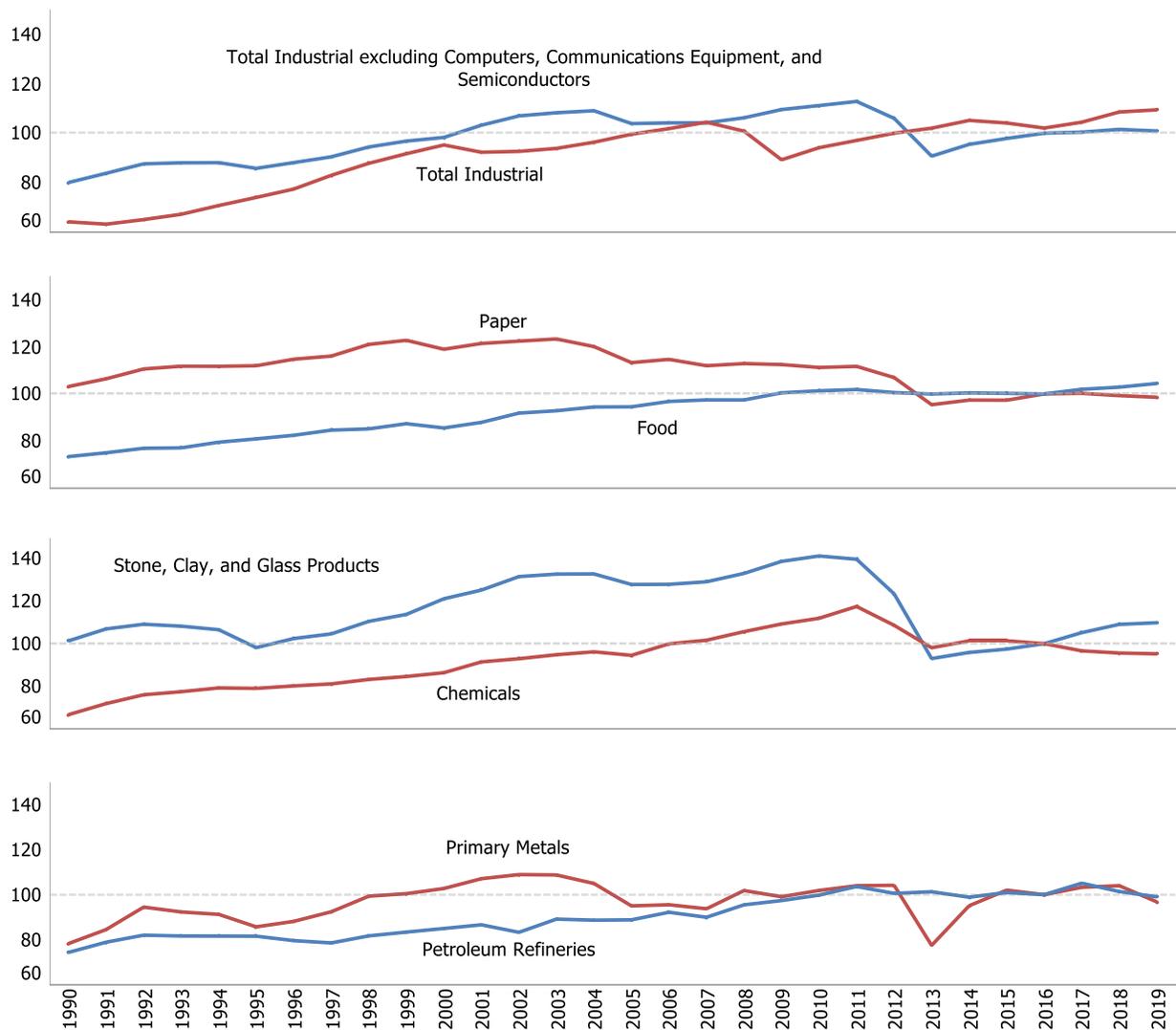
Figure 3-12: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO₂ Emissions (Including Electricity)
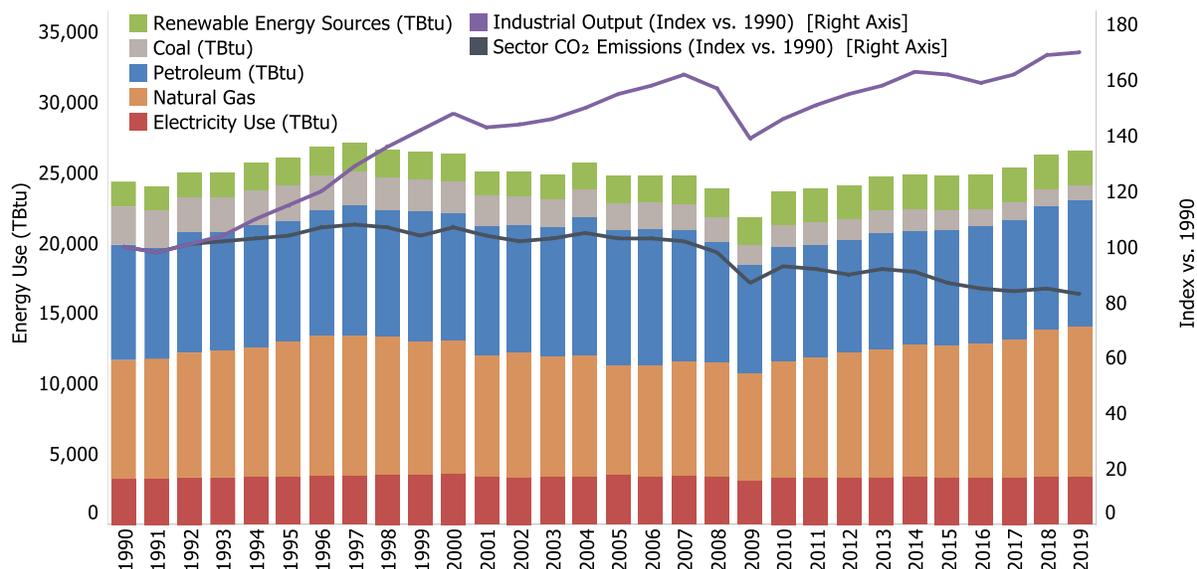
Despite the growth in industrial output (70 percent) and the overall U.S. economy (104 percent) from 1990 to 2019, direct CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 3.7 percent over the same time series (see Figure 3-12). A number of factors are assumed to result in decoupling of growth in industrial output from industrial greenhouse gas emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon intensive than the older methods.

Box 3-3: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2019 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the Inventory's use of EIA national fuel statistics to meet the UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise. [19]

As with previous Inventory reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the Inventory to the

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[19] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

UNFCCC, progress was made on certain fuel types for specific industries and has been included in the CRF tables that are submitted to the UNFCCC along with this report.[20] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the Common Reporting Format (CRF) tables should be viewed as an initial attempt at this exercise. Additional efforts will be made for future Inventory reports to improve the mapping of fuel types and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRF tables. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2019 time period in the CRF tables. It is believed that the current analysis has led to improvements in the presentation of data in the Inventory, but further work will be conducted, and future improvements will be realized in subsequent Inventory reports. This includes incorporating the latest MECS data as it becomes available.

Residential and Commercial Sectors

Emissions from the residential and commercial sectors have generally decreased since 1990. Short-term trends are often correlated with seasonal fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Population growth and a trend towards larger houses has led to increasing energy use over the time series, while population migration to warmer areas and improved energy efficiency and building insulation have slowed the increase in energy use in recent years. Starting in around 2014, energy use and emissions begin to decouple due to decarbonization of the electric power sector (see Figure 3-13).

Figure 3-13: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)
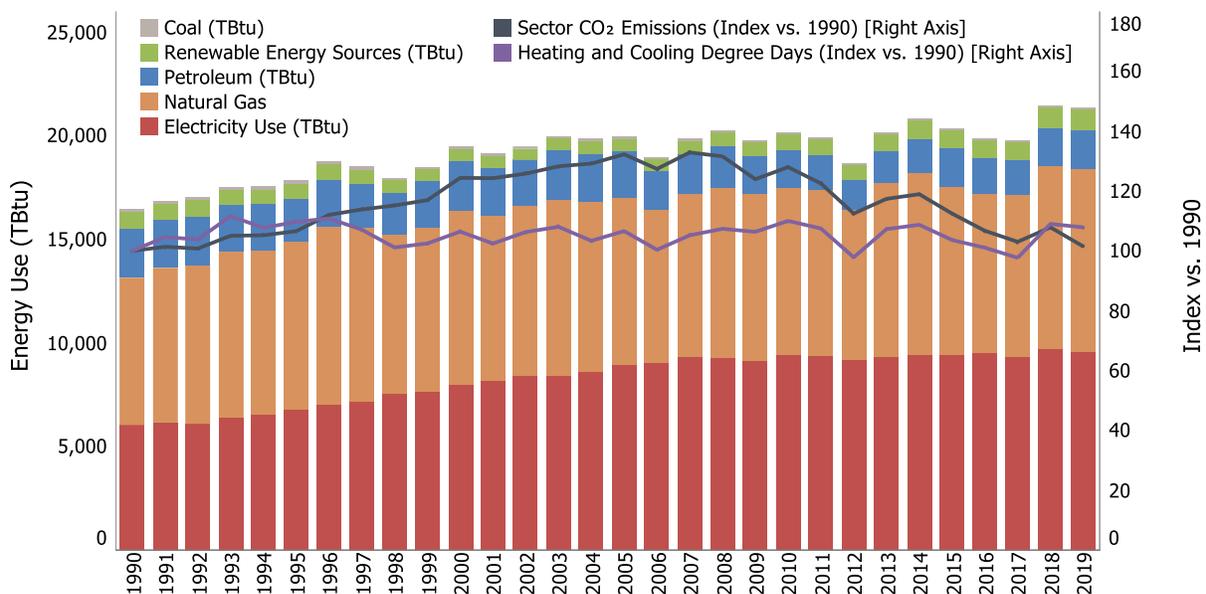
In 2019 the residential and commercial sectors accounted for 7 and 5 percent of CO_2 emissions from fossil fuel combustion, respectively; 42 and 11 percent of CH_4 emissions from fossil fuel combustion, respectively; and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs.

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[20] See <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>.

Coal consumption was a minor component of energy use in the commercial sector and did not contribute to any energy use in the residential sector. In 2019, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 933.9 MMT CO_2 Eq. and 811.4 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from combined fossil fuel combustion and electricity use within the residential and commercial end-use sectors decreased by 6.1 and 5.8 percent from 2018 to 2019, respectively. A slight increase in heating degree days (0.6 percent) impacted energy demand for heating in the residential and commercial sectors. This was partially offset by a 5.4 percent decrease in cooling degree days compared to 2018, which reduced demand for air conditioning in the residential and commercial sectors. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has contributed to a decrease in energy demand in households (EIA 2020g), resulting in a decrease in energy-related emissions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in total housing units and building attributes (e.g., larger sizes and improved insulation).

In 2019, combustion emissions from natural gas consumption represented 82 and 77 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Carbon dioxide emissions from natural gas combustion in the residential and commercial sectors in 2019 increased by 0.5 percent and 0.1 percent from 2018 to 2019, respectively.

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will occur across all sectors and sources including stationary, transportation and mobile combustion sources.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 3-11. Table 3-10 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,842.3 MMT CO_2 Eq. in 2019, which represented 36 percent of CO_2 emissions, 22 percent of CH_4 emissions, and 42 percent of N_2O emissions from fossil fuel combustion, respectively.[21] Fuel purchased in the United States for international aircraft and marine travel accounted for an additional 117.2 MMT CO_2 Eq. in 2019; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2019, transportation emissions from fossil fuel combustion rose by 21 percent due, in large part, to increased demand for travel (see Figure 3-14). The number of vehicle miles traveled (VMT) by light-duty motor

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[21] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

vehicles (passenger cars and light-duty trucks) increased 47 percent from 1990 to 2019,[22] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices.

From 2018 to 2019, CO_2 emissions from the transportation end-use sector increased by 0.04 percent. The small increase in emissions is primarily attributed to an increase in non-road fuel use, particularly jet fuel consumption.

Commercial aircraft emissions increased by 3.5 percent between 2018 and 2019, but have decreased 4 percent since 2007 (FAA 2021).[23] Decreases in jet fuel emissions (excluding bunkers) since 2007 are due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 24 percent from 1990 to 2019. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Figure 3-14: Fuels Used in Transportation Sector, Onroad VMT, and Total Sector CO₂ Emissions
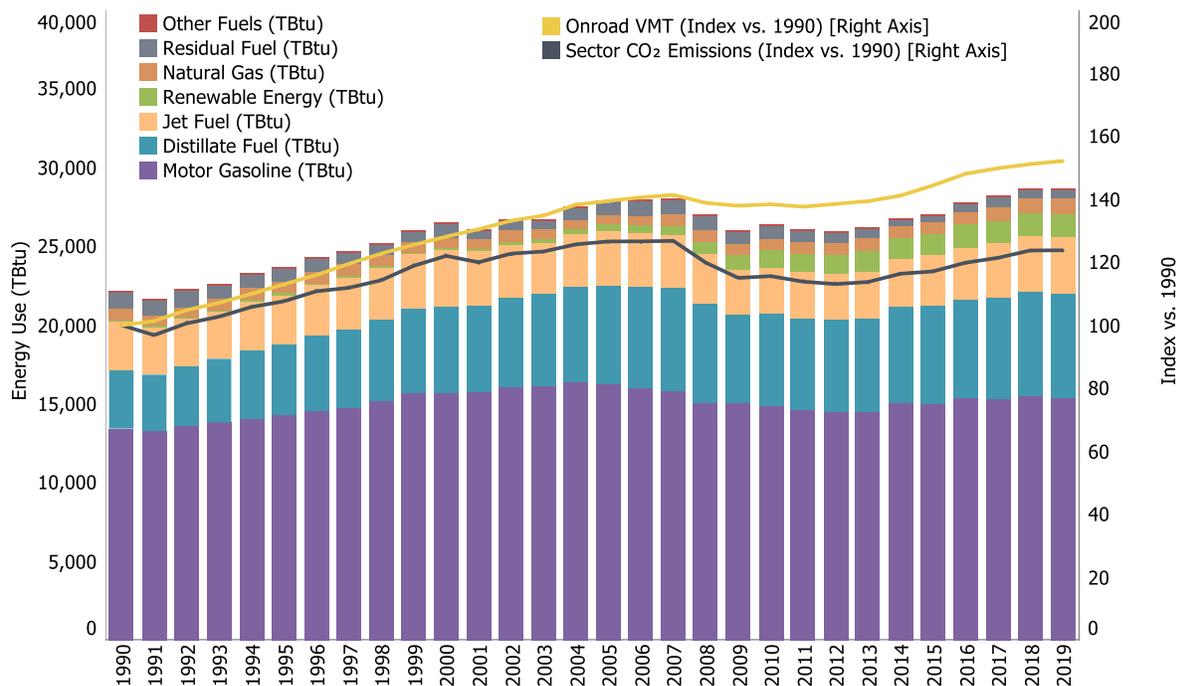
Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels. Other Fuels includes aviation gasoline and propane. Source: Information on fuel consumption was obtained from EIA (2019a).

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[22] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2019). In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2019 time period. In absence of these method changes, light-duty VMT growth between 1990 and 2019 would likely have been even higher.

[23] Commercial aircraft, as modeled in FAA's AEDT (FAA 2021), consists of passenger aircraft, cargo, and other chartered flights.

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 24 percent (349.8 MMT CO_2) between 1990 and 2019, an annualized increase of 0.8 percent. Among domestic transportation sources in 2019, light-duty vehicles (including passenger cars and light-duty trucks) represented 58 percent of CO_2 emissions from fossil fuel combustion, medium- and heavy-duty trucks and buses 25 percent, commercial aircraft 7 percent, and other sources 10 percent. See Table 3-13 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other Inventory sectors.[24] Ethanol consumption by the transportation sector has increased from 0.7 billion gallons in 1990 to 13.6 billion gallons in 2019, while biodiesel consumption has increased from 0.01 billion gallons in 2001 to 1.8 billion gallons in 2019. For additional information, see Section 3.11 on biofuel consumption at the end of this chapter and Table A-81 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,052.6 MMT CO_2 in 2019. This is an increase of 14 percent (128.1 MMT CO_2) from 1990 due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2019). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,154.7 MMT CO_2 in 2004, and since then have declined about 9 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (Figure 3-15) reflects the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty vehicle VMT grew only modestly for much of the period. Light-duty vehicle VMT grew by less than one percent or declined each year between 2005 and 2013,[25] then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2017, the rate of light-duty vehicle VMT growth slowed to less than one percent each year. Average new vehicle fuel economy has increased almost every year since 2005, while the light-duty truck share decreased to about 33 percent in 2009 and has since varied from year to year between 36 and 56 percent. Since 2014, light-duty truck share has slowly increased and is about 56 percent of new vehicles sales in model year 2019 (EPA 2019b). See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

Medium- and heavy-duty truck CO_2 emissions increased by 90 percent from 1990 to 2019. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 109 percent between 1990 and 2019.[26] Carbon dioxide from the domestic operation of commercial aircraft increased by 22 percent (24.3 MMT CO_2) from 1990 to 2019.[27] Across all categories of aviation, excluding international bunkers, CO_2 emissions

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[24] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See <https://www.epa.gov/renewable-fuel-standard-program>.

[25] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2019). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2019 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

[26] While FHWA data shows consistent growth in medium- and heavy-duty truck VMT over the 1990 to 2019 time period, part of the growth reflects a method change for estimating VMT starting in 2007. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class, thus leading to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2019 time period. During the time period prior to the method change (1990 to 2006), VMT for medium- and heavy-duty trucks increased by 51 percent.

[27] Commercial aircraft, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

decreased by 4 percent (7.9 MMT CO_2) between 1990 and 2019.[28] This includes a 66 percent (23.1 MMT CO_2) decrease in CO_2 emissions from domestic military operations.

Transportation sources also produce CH_4 and N_2O; these emissions are included in Table 3-14 and Table 3-15 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

Figure 3-15: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2019
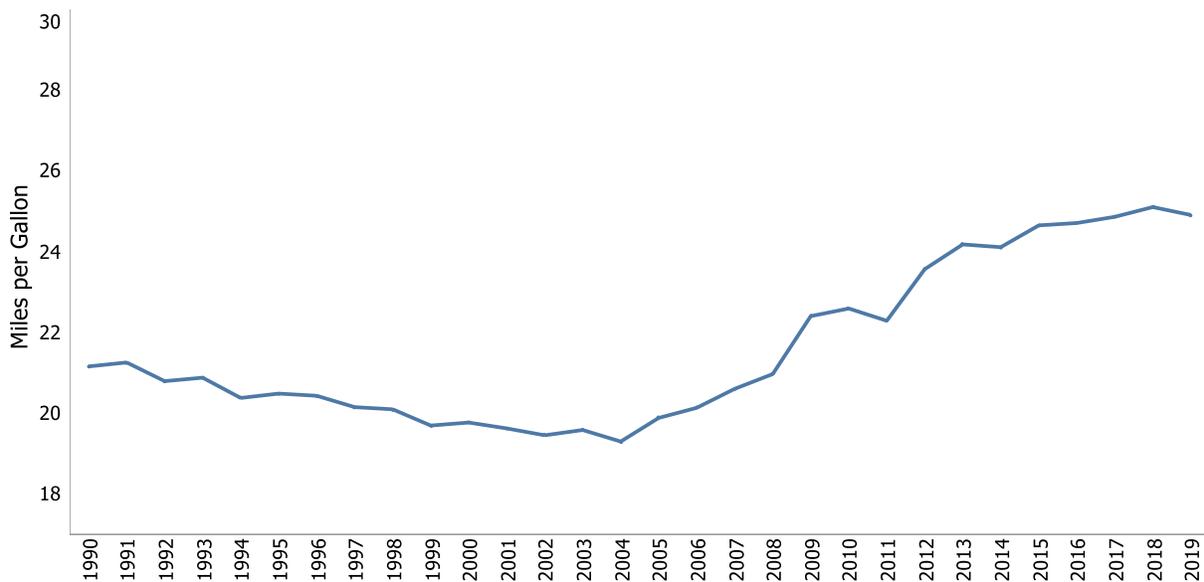
Source: EPA (2020a).

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[28] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-16: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2019
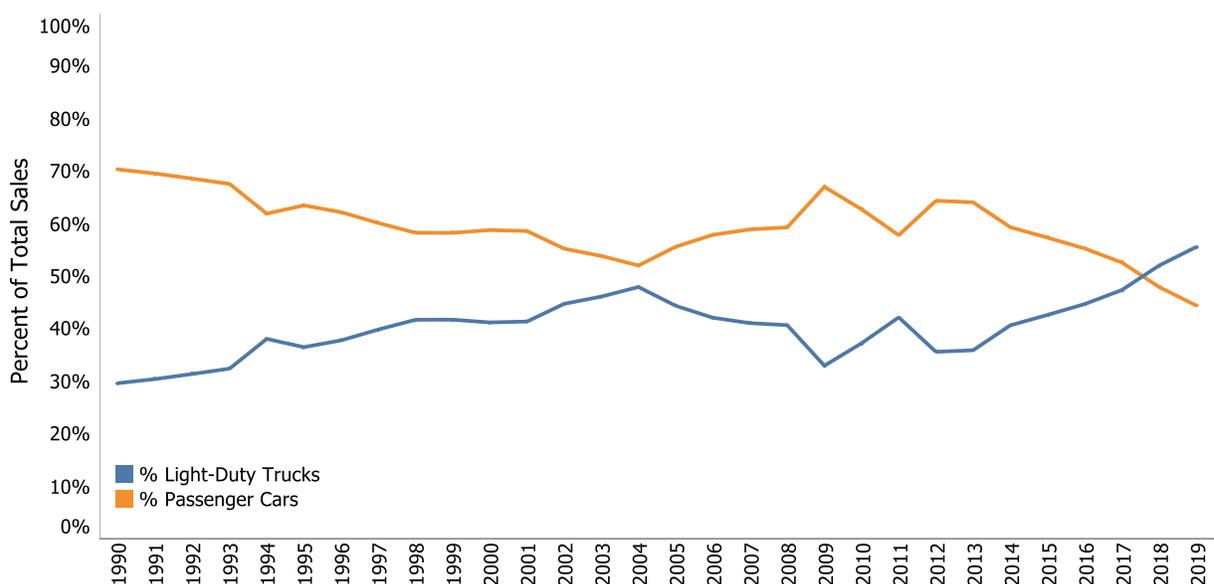
Source: EPA (2019b).

Table 3-13: CO₂ Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO₂ Eq.)

Fuel/Vehicle Type	1990	2005	2015[a]	2016[a]	2017[a]	2018[a]	2019[a]
Gasoline[b]	**958.9**	**1,150.1**	**1,058.6**	**1,084.8**	**1,081.8**	**1,097.1**	**1,086.8**
Passenger Cars	604.3	637.1	724.3	737.8	737.4	748.8	742.3
Light-Duty Trucks	300.6	463.5	280.5	291.8	288.2	290.9	289.1
Medium- and Heavy-Duty Trucks[c]	37.7	33.8	38.9	40.0	40.9	41.9	40.1
Buses	0.3	0.4	0.9	0.9	0.9	1.0	1.0
Motorcycles	1.7	1.6	3.6	3.8	3.7	3.8	3.6
Recreational Boats[d]	14.3	13.7	10.5	10.6	10.6	10.7	10.7
Distillate Fuel Oil (Diesel)[b]	**262.9**	**462.6**	**457.5**	**454.2**	**468.3**	**480.2**	**481.1**
Passenger Cars	7.9	4.3	4.3	4.3	4.3	4.4	4.6
Light-Duty Trucks	11.5	26.1	13.8	14.1	14.1	14.2	14.9
Medium- and Heavy-Duty Trucks[c]	190.5	364.2	366.8	369.3	381.6	390.9	394.8
Buses	8.0	10.7	17.0	16.6	17.9	19.1	19.3
Rail	35.5	46.1	39.8	36.3	37.5	39.4	37.1
Recreational Boats[d]	2.7	2.9	2.6	2.7	2.8	2.9	2.9
Ships and Non-Recreational Boats[e]	6.8	8.4	13.2	10.9	10.1	9.4	7.6
International Bunker Fuels[f]	11.7	9.5	8.4	8.7	9.0	10.0	10.1
Jet Fuel	**184.2**	**189.3**	**157.6**	**166.0**	**171.8**	**172.3**	**177.8**
Commercial Aircraft[g]	109.9	132.7	119.0	120.4	128.0	129.6	134.2
Military Aircraft	35.0	19.4	13.5	12.3	12.2	11.8	11.9
General Aviation Aircraft	39.4	37.3	25.1	33.4	31.5	30.9	31.7
International Bunker Fuels[f]	38.0	60.1	71.9	74.1	77.7	80.8	80.7
International Bunker Fuels from Commercial Aviation	30.0	55.6	68.6	70.8	74.5	77.7	77.6
Aviation Gasoline	**3.1**	**2.4**	**1.5**	**1.4**	**1.4**	**1.5**	**1.6**
General Aviation Aircraft	3.1	2.4	1.5	1.4	1.4	1.5	1.6

Residual Fuel Oil	**22.6**		**19.3**		**4.2**	**12.9**	**16.5**	**14.0**	**14.7**
Ships and Boats[e]	22.6		19.3		4.2	12.9	16.5	14.0	14.7
International Bunker Fuels[f]	53.7		43.6		30.6	33.8	33.4	31.4	25.2
Natural Gas[j]	**36.0**		**33.1**		**39.4**	**40.1**	**42.3**	**50.9**	**54.8**
Passenger Cars	+		+		+	+	+	+	+
Light-Duty Trucks	+		+		+	+	+	+	+
Medium- and Heavy-Duty Trucks	+		+		+	+	+	+	+
Buses	+		0.6		0.9	0.8	0.9	0.9	1.0
Pipeline[h]	36.0		32.4		38.5	39.2	41.3	49.9	53.7
LPG[j]	**1.4**		**1.8**		**0.4**	**0.4**	**0.4**	**0.5**	**0.5**
Passenger Cars	+		+		+	+	+	+	+
Light-Duty Trucks	0.2		0.3		0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Trucks[c]	1.1		1.3		0.3	0.3	0.3	0.3	0.3
Buses	0.1		0.1		+	0.1	0.1	0.1	0.1
Electricity[j]	**3.0**		**4.7**		**4.3**	**4.2**	**4.3**	**4.7**	**4.7**
Passenger Cars	+		+		0.5	0.6	0.8	1.2	1.4
Light-Duty Trucks	+		+		+	0.1	0.1	0.2	0.2
Buses	+		+		+	+	+	+	+
Rail	3.0		4.7		3.7	3.5	3.4	3.3	3.1
Total[k]	**1,472.2**		**1,863.4**		**1,723.5**	**1,764.1**	**1,786.8**	**1,821.2**	**1,821.9**
Total (Including Bunkers)[f]	**1,575.6**		**1,976.6**		**1,834.4**	**1,880.7**	**1,906.9**	**1,943.3**	**1,938.0**
Biofuels-Ethanol[i]	4.1		21.6		74.2	76.9	77.7	78.6	78.7
Biofuels-Biodiesel[i]	+		0.9		14.1	19.6	18.7	17.9	17.1

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the Inventory. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2019 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[b] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-27 and VM-1 (FHWA 1996 through 2019). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2018). TEDB data for 2019 has not been published yet, therefore 2018 data are used as a proxy.

[c] Includes medium- and heavy-duty trucks over 8,500 lbs.

[d] In 2014, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the Nonroad component of MOVES2014b for years 1999 through 2019.

[e] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[f] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates including international bunker fuel-related emissions are presented for informational purposes.

[g] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[h] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[i] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.11 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[j] Transportation sector natural gas and LPG consumption are based on data from EIA (2019b). Prior to the 1990 to 2015 Inventory, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by

passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 to 2016 Inventory and apply to the 1990 to 2019 time period.

k Includes emissions from rail electricity.

l Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales and engine efficiency data, as outlined in Browning (2018a). In prior Inventory years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes apply to the 2010 through 2019 time period.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. Inventory with the exception of pipelines and electric locomotives;[29] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.).[30] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-14 and Table 3-15 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[31]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) and was the fifth largest source of national N_2O emissions (4.4 percent). From 1990 to 2019, mobile source CH_4 emissions declined by 63 percent, to 2.4 MMT CO_2 Eq. (95 kt CH_4), due largely to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 60 percent from 1990 to 2019, to 18.0 MMT CO_2 Eq. (60 kt N_2O). Earlier generation emissions control technologies initially resulted in higher N_2O emissions, causing a 29 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emissions control technologies have reduced N_2O emissions, resulting in a 69 percent decrease in mobile source N_2O emissions from 1997 to 2019 (Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks and non-highway sources. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

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[29] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[30] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (Transportation, Industrial, Commercial, Residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the Transportation end-use sector). CH_4 and N_2O emissions are reported using the "Mobile Combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[31] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2019.

Figure 3-17: Mobile Source CH₄ and N₂O Emissions
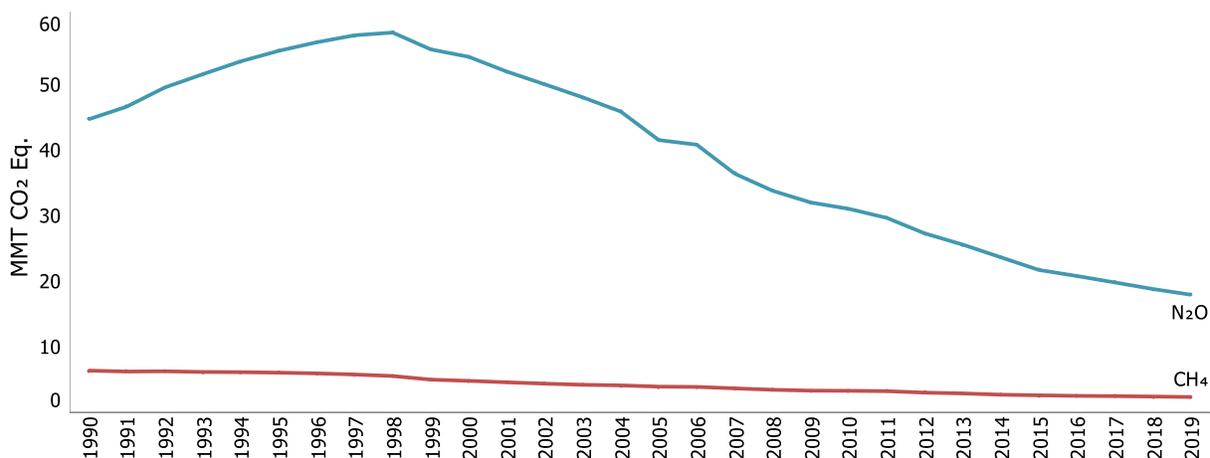
Table 3-14: CH₄ Emissions from Mobile Combustion (MMT CO₂ Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2015	2016	2017	2018	2019
Gasoline On-Road[b]	**5.2**	**2.2**	**1.0**	**0.9**	**0.8**	**0.7**	**0.7**
Passenger Cars	3.2	1.3	0.6	0.6	0.5	0.5	0.4
Light-Duty Trucks	1.7	0.8	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks and Buses	0.3	0.1	0.1	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	0.1	0.1	0.1	0.1
Alternative Fuel On-Road	**+**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Road[c]	**1.2**	**1.5**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**
Ships and Boats	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Rail	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[d]	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[e]	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Other[f]	0.4	0.6	0.6	0.6	0.6	0.6	0.6
Total	**6.4**	**4.0**	**2.6**	**2.5**	**2.5**	**2.4**	**2.4**

Notes: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2019 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO₂ Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1.

[c] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 to 2017 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

d Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

e Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

f "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table 3-15: N$_2$O Emissions from Mobile Combustion (MMT CO$_2$ Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2015	2016	2017	2018	2019
Gasoline On-Road[b]	**37.5**	**31.8**	**11.6**	**10.2**	**8.7**	**7.3**	**6.2**
Passenger Cars	24.1	17.3	8.0	7.0	6.0	5.1	4.3
Light-Duty Trucks	12.8	13.6	3.1	2.7	2.3	1.9	1.6
Medium- and Heavy-Duty Trucks and Buses	0.5	0.9	0.4	0.4	0.3	0.3	0.2
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**0.2**	**0.3**	**2.1**	**2.4**	**2.6**	**2.8**	**3.0**
Passenger Cars	+	+	+	0.1	0.1	0.1	0.1
Light-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Trucks and Buses	0.2	0.3	2.0	2.2	2.5	2.7	2.8
Alternative Fuel On-Road	**+**	**+**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Road	**7.1**	**9.4**	**7.9**	**8.1**	**8.4**	**8.5**	**8.7**
Ships and Boats	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Rail[c]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Aircraft	1.7	1.8	1.5	1.5	1.6	1.6	1.6
Agricultural Equipment[d]	1.3	1.6	1.1	1.1	1.1	1.1	1.1
Construction/Mining Equipment[e]	1.3	2.1	1.5	1.6	1.7	1.8	1.9
Other[f]	2.2	3.3	3.3	3.4	3.4	3.5	3.6
Total	**44.7**	**41.6**	**21.7**	**20.8**	**19.8**	**18.8**	**18.0**

Notes: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2019 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO$_2$ Eq.
a See Annex 3.2 for definitions of on-road vehicle types.
b Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1.
c Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014-2017 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.
d Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
e Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
f "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

CO$_2$ from Fossil Fuel Combustion

Methodology

CO$_2$ emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) with some exceptions as discussed below.[32] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* (EIA 2020c). EIA data include fuel consumption statistics from the 50 U.S. states and the District of Columbia, including tribal lands. The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2020e).[33]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this Inventory are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption datasets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[34]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[35]

2. *Subtract uses accounted for in the Industrial Processes and Product Use chapter*. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2020), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2020a, 2020c, 2020d), USAA (2008 through 2020), USGS (1991 through 2017), (USGS 2019), USGS (2014 through 2020a), USGS (2014 through 2020b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001, 2002, 2007), USGS (2020a), USGS (1991 through 2015a), USGS (1991

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[32] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[33] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 24.6 MMT CO$_2$ Eq. in 2019.

[34] See IPCC Reference Approach for Estimating CO$_2$ Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[35] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

through 2017a), USGS (2014 through 2020a), USGS (1991 through 2015b), USGS (2020b), USGS (1991 through 2017).[36]

3. *Adjust for biofuels and petroleum denaturant*. Fossil fuel consumption estimates are adjusted downward to exclude fuels with biogenic origins and avoid double counting in petroleum data statistics. Carbon dioxide emissions from ethanol added to motor gasoline and biodiesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol and biodiesel.[37] For the years 1993 through 2008, petroleum denaturant is currently included in EIA statistics for both natural gasoline and finished motor gasoline. To avoid double counting, petroleum denaturant is subtracted from finished motor gasoline for these years.[38]

4. *Adjust for exports of CO_2.* Since October 2000, the Dakota Gasification Plant has been exporting CO_2 produced in the coal gasification process to Canada by pipeline. Because this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from EIA (2020d) coal consumption statistics that are used to calculate greenhouse gas emissions from the Energy Sector. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, data for CO_2 exports were collected from Environment and Climate Change Canada (2020). A discussion of the methodology used to estimate the amount of CO_2 captured and exported by pipeline is presented in Annex 2.1.

5. *Adjust sectoral allocation of distillate fuel oil and motor gasoline.* EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2018), Benson (2002 through 2004), DOE (1993 through 2017), EIA (2007), EIA (1991 through 2019), EPA (2018), and FHWA (1996 through 2018).[39]

6. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the C contained in the fuel for a period of time. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion (since the C in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section 3.2 – Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption were provided by EIA (2020c).

7. *Subtract consumption of international bunker fuels.* According to the UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from

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[36] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

[37] Natural gas energy statistics from EIA (2020g) are already adjusted downward to account for biogas in natural gas.

[38] These adjustments are explained in greater detail in Annex 2.1.

[39] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2019).

international transport activities were calculated separately following the same procedures used to calculate emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of Carbon content).[40] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2020) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2021); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2019) for 1990 through 2001 and 2007 through 2018, and DHS (2008) for 2003 through 2006.[41] Consumption of these fuels was subtracted from the corresponding fuels totals in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.10 – International Bunker Fuels.

8. *Determine the total Carbon content of fuels consumed.* Total C was estimated by multiplying the amount of fuel consumed by the amount of C in each fuel. This total C estimate defines the maximum amount of C that could potentially be released to the atmosphere if all of the C in each fuel was converted to CO_2. A discussion of the methodology and sources used to develop the C content coefficients are presented in Annexes 2.1 and 2.2.

9. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the Carbon content of the fuels consumed, and the fraction of C that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1). Carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to C (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT).

10. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2020c) and USAF (1998).[42]

   - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2019); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2018). [43,44]

   - For non-road vehicles, activity data were obtained from AAR (2008 through 2019), APTA (2007 through 2018), APTA (2006), BEA (2020), Benson (2002 through 2004), DLA Energy (2019), DOC (1991 through 2019), DOE (1993 through 2017), DOT (1991 through 2019), EIA (2009a), EIA (2020c), EIA

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[40] See International Bunker Fuels section in this chapter for a more detailed discussion.

[41] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[42] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

[43] Data from FHWA's Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2017). In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the time period from 2007 through 2019. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[44] Transportation sector natural gas and LPG consumption are based on data from EIA (2020g). In previous Inventory years, data from DOE (1993 through 2017) TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the previous Inventory and apply to the time period from 1990 to 2015.

(2019f), EIA (1991 through 2019), EPA (2018),[45] and Gaffney (2007).

- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Box 3-4: Carbon Intensity of U.S. Energy Consumption

The amount of C emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that C that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke (see Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels). In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

Table 3-16 provides a time series of the carbon intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-16 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher C intensities over this period. The Carbon intensity of the transportation sector was closely related to the Carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./QBtu), which were the primary sources of energy. Lastly, the electric power sector had the highest Carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-16: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

Sector	1990	2005	2015	2016	2017	2018	2019
Residential[a]	57.4	56.8	55.5	55.2	55.1	55.3	55.1
Commercial[a]	59.7	57.8	57.1	56.7	56.5	56.0	56.1
Industrial[a]	64.5	64.6	61.4	61.0	60.8	60.5	60.3
Transportation[a]	71.1	71.5	71.1	71.1	71.2	71.0	71.0
Electric Power[b]	87.3	85.8	78.1	76.8	77.3	75.5	73.0
U.S. Territories[c]	72.3	72.6	72.0	71.0	71.3	71.3	71.3
All Sectors[c]	**73.1**	**73.6**	**69.6**	**69.2**	**69.1**	**68.3**	**67.3**

Note: Excludes non-energy fuel use emissions and consumption.
[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.

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[45] In 2014, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the Nonroad component of MOVES2014b for years 1999 through 2019.

For the time period of 1990 through about 2008, the carbon intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the carbon intensity has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2019, was approximately 9.8 percent below levels in 1990 (see Figure 3-18). To differentiate these estimates from those of Table 3-16, the carbon intensity trend shown in Figure 3-18 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2018).

Figure 3-18: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP
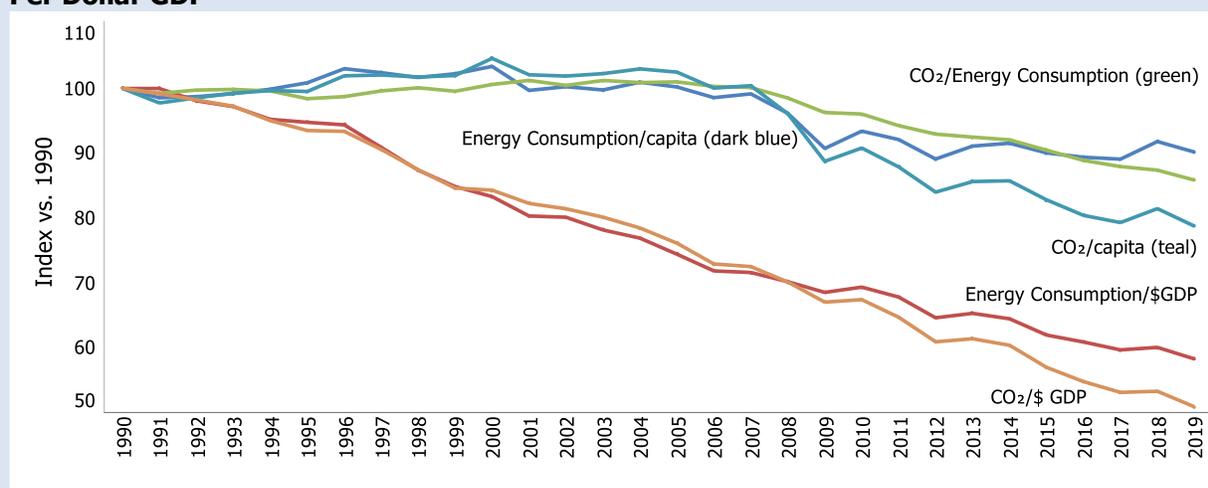
Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2020c), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty and Time-Series Consistency

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply.

Although national statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is

less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor challenges in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with C emitted from Non-Energy Uses of Fossil Fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.10 – International Bunker Fuels). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 170 input variables were modeled for CO_2 from energy-related Fossil Fuel Combustion (including about 20 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[46] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[47]

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[48] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte

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[46] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[47] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[48] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2019 were estimated to be between 4,757.7 and 5,073.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 4 percent above the 2019 emission estimate of 4,856.7 MMT CO_2 Eq.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

| Fuel/Sector | 2019 Emission Estimate (MMT CO_2 Eq.) | Uncertainty Range Relative to Emission Estimate[a] | | | |
| | | (MMT CO_2 Eq.) | | (%) | |
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**1,027.1**	**991.9**	**1,125.1**	**-3%**	**10%**
Residential	NO	NO	NO	NO	NO
Commercial	1.6	1.5	1.8	-5%	15%
Industrial	49.5	47.1	57.2	-5%	16%
Transportation	NO	NO	NO	NO	NO
Electric Power	973.5	935.8	1,068.4	-4%	10%
U.S. Territories	2.5	2.2	3.0	-12%	19%
Natural Gas[b]	**1,644.6**	**1,625.8**	**1,720.0**	**-1%**	**5%**
Residential	275.3	267.5	294.6	-3%	7%
Commercial	192.8	187.4	206.3	-3%	7%
Industrial	503.3	486.5	540.5	-3%	7%
Transportation	54.8	53.2	58.6	-3%	7%
Electric Power	616.0	598.2	647.4	-3%	5%
U.S. Territories	2.5	2.2	3.0	-12%	17%
Petroleum[b]	**2,184.6**	**2,054.4**	**2,313.2**	**-6%**	**6%**
Residential	61.5	58.0	64.8	-6%	5%
Commercial	55.3	52.3	58.1	-5%	5%
Industrial	269.7	215.7	324.3	-20%	20%
Transportation	1,762.5	1,649.9	1,873.9	-6%	6%
Electric Power	16.2	15.4	17.5	-5%	8%
U.S. Territories	19.5	18.0	21.7	-8%	11%
Total (excluding Geothermal)[b]	**4,856.3**	**4,757.1**	**5,072.4**	**-2%**	**4%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Electric Power	0.4	NE	NE	NE	NE
Total (including Geothermal)[b,c]	**4,856.7**	**4,757.7**	**5,073.0**	**-2%**	**4%**

Note: Totals may not sum due to independent rounding.

NO (Not Occurring)

NE (Not Estimated)

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

[c] Geothermal emissions added for reporting purposes, but an uncertainty analysis was not performed for CO_2 emissions from geothermal production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid

fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the CO_2 emission estimates from fossil fuel combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. The reference approach (detailed in Annex 4) uses alternative methodologies and different data sources than those contained in this section of the report. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that was not stored during non-energy use of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are not subtracted in the reference approach. As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the Non-Energy Use (NEU) source category emissions are included in the reference approach (see Annex 4 for more details).

Recalculations Discussion

Several updates to activity data and emission factors lead to recalculations of previous year results. The major updates are as follows:

- EIA (2020c) updated energy consumption statistics across the time series relative to the previous Inventory. As a result of revised natural gas heat contents, EIA updated natural gas consumption in the residential, commercial, and industrial sectors for 2018. Approximate heat rates for electricity and the heat content of electricity were revised for natural gas and noncombustible renewable energy, which impacted electric power energy consumption by sector. EIA also revised sector allocations for distillate fuel oil, residual fuel oil, and kerosene for 2018, and for propane for 2010 through 2012, 2014, 2017, and 2018, which impacted LPG by sector. EIA revised product supplied totals for crude oil and petroleum products, which impacted the nonfuel sequestration statistics, particularly for lubricants for 2018 and LPG for 2010 through 2018 relative to the previous Inventory. This resulted in a slight decrease in energy used in the industrial sector.
- To align with EIA's methodology for calculating motor gasoline consumption, petroleum denaturant adjustments to motor gasoline consumption for the period 1993 through 2008 were corrected. This resulted in an average annual decrease of 6.2 TBtu in motor gasoline consumption for the period 1993 through 2008, which led to a decrease in emissions from gasoline consumption in those years because denaturant emissions were previously being double counted.
- Newly published U.S. Territories data from EIA (2020e) was integrated, which impacted total estimates for U.S. Territories across the time series. This resulted in the following observed changes:
  - average annual decrease of 0.3 MMT CO_2 Eq. (21.3 percent) in coal use across the time series;
  - decrease of 0.01 MMT CO_2 Eq. (0.48 percent) in natural gas use across the time series; and
  - decrease in petroleum use from 1990 through 1999, increase in petroleum use from 2000 through 2008, then a decrease from 2009 through 2018, resulting in an average annual decrease of 5.8 MMT CO_2 eq. (17.9 percent) in petroleum use across the time series.

- Updated MECS data for 2018 resulted in an increase in natural gas used in non-energy use. This resulted in a decrease in natural gas used in the industrial sector as part of fossil fuel combustion estimates. The updates mainly impacted years 2014-2018. See Section 3.2 for more details on NEU emissions and adjustments.
- EPA (2020c) revised distillate fuel oil and motor gasoline carbon contents, which impacted petroleum consumption in the transportation, residential, commercial, and industrial sectors. The combined effect of both the diesel fuel and gasoline emission factor update was an increase in emissions early in the time series and then decreases in emissions in more recent years. For years 1990 through 2005, the average annual increase in total emissions was approximately 7 MMT CO_2 (0.1 percent of emissions). For the years 2006 to 2018 the average annual decrease in total emissions is about 5 MMT CO_2 (less than 0.1 percent of emissions).
- EPA also revised HGL C contents to align with EIA's revised heat contents and HGL fuel type categorization (EIA 2020c; ICF 2020). A discussion of the methodology used to develop the C content coefficients is presented in Annex 2.2. This resulted in an average annual increase of 3.0 percent in the weighted industrial HGL C contents.
- To account for coal consumed during the production of coke oven gas (COG) and blast furnace gas (BFG) for energy purposes (e.g., as an input to the natural gas distribution system), consumption of COG and BFG was included in industrial coal consumption estimates in the energy sector, in alignment with EIA's methodology (EIA 2020c). Previously, COG and BFG consumption that enters the natural gas distribution system was removed from industrial natural gas consumption estimates in the energy sector. These adjustments are explained in greater detail in Annex 2.1. This resulted in an average annual increase of 1.5 TBtu (48 percent) in coal use between 1990 through 1992, no change between 1993 through 1999, an average annual decrease of 0.5 TBtu (146 percent) between 2000 and 2001, and no change from 2002 forward.
- The Dakota Gasification Plant uses a coal gasification process that produces synthetic natural gas (SNG) from lignite coal. Coal consumption at this plant is included in EIA's statistics for industrial coal consumption, which is used to estimate CO_2 emissions from coal combustion in the U.S. Inventory. Previously, coal consumption for the production of SNG was subtracted from industrial coal consumption statistics. However, SNG is not included in industrial natural gas consumption data in EIA's MER and rather, SNG is accounted for in its primary energy category (e.g., gasification of coal). To account for SNG from coal gasification, the adjustment to industrial coal consumption to subtract the quantity of SNG produced was removed. These adjustments are explained in greater detail in Annex 2.1. This resulted in an average annual increase in coal use across the time series of 31.9 Tbtu (3 percent).
- The Dakota Gasification Plant also produces CO_2 as a byproduct. A fraction of the plant's total site-generated CO_2 that is captured by the plant's CO_2 capture system is exported by pipeline to Canada. The remainder of the byproduct CO_2 is emitted to the atmosphere. Because the exported CO_2 is not emitted to the atmosphere in the United States, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from the EIA industrial coal consumption statistics used in the Inventory, so that the amount of CO_2 exported is not included in the reported greenhouse gas emissions from the Energy Sector. Previously, the amount of CO_2 captured and exported by pipeline annually was estimated from publicly available data for plant operations, including historical CO_2 export data and the publicly reported transport (CO_2 gas compressor) capacity of the CO_2 pipeline, assuming that the CO_2 pipeline operates at 100 percent of the pipeline's transport capacity. To ensure consistency in reporting between the Inventory and the Canadian National Greenhouse Gas Inventory, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 has been revised to align with the Canadian National Greenhouse Gas Inventory (Environment and Climate Change Canada 2020). These adjustments are explained in greater detail in Annex 2.1. This resulted in an average decrease of 0.7 MMT CO_2 Eq. (10 percent) in the amount of CO_2 exported each year between 2000 and 2018 and therefore an increase in coal use across the time series.

All of the revisions discussed above resulted in the following impacts on emissions over time by fuel type:

- Coal emissions increased by an average annual amount of 2.8 MMT CO_2 Eq. (0.2 percent increase of emissions from coal) across the entire time series. This is primarily due to the update to the adjustment for COG and BFG and the change in CO_2 export data.
- There was a slight average annual increase in natural gas emissions from 1990 to 2006 of 0.2 MMT CO_2 Eq. (less than 0.1 percent of natural gas emissions). This is mainly due to the removal of the COG and BFG adjustment from industrial natural gas consumption. There was a bigger average annual decrease in emissions of 5.0 MMT CO_2 Eq. (0.3 percent) from 2007 to 2018. The decrease is much larger in the latter years due to the update of the 2018 MECS data, which increases natural gas use as NEU in the industrial sector.
- Petroleum emissions decreased by an average annual amount of 15.3 MMT CO_2 Eq. (0.7 percent of petroleum emissions) from 1990 to 1999, which is mainly due to decreased emissions in the industrial sector as a result of the update in the weighted industrial HGL C contents and the decrease in petroleum use from the updated data for U.S. Territories.
- Petroleum emissions increased by an average annual amount of 14.5 MMT CO_2 Eq. (0.6 percent) from 2000 to 2007. This is mainly due to an increase in petroleum emissions in U.S. Territories from the newly integrated data and increased emissions in the Transportation sector due to changes in accounting for denaturants and updates in the distillate fuel oil and motor gasoline emissions factors.
- Finally, petroleum emissions decreased at the end of the time series by an average annual amount of 15.8 MMT CO_2 Eq. (0.7 percent) from 2008 to 2018. This is mainly due to the decrease in petroleum use from the newly integrated data for U.S. Territories and decreases across the other sectors based on updated gasoline and diesel fuel emission factors.

Overall, these changes resulted in an average annual decrease of 6.4 MMT CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2018, relative to the previous Inventory. However, there were bigger absolute changes across the time series as discussed above by fuel type. The changes in petroleum emissions drive the overall change in emissions from the recalculations across time.

Planned Improvements

To reduce uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from U.S. Territories.

The availability of facility-level combustion emissions through EPA's GHGRP will continue to be examined to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC methodologies, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[49] In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory.

Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, efforts will be taken to incorporate updated industrial fuel consumption data from EIA's Manufacturing Energy Consumption Survey (MECS), with updated data for 2018. Additional work will look at CO_2 emissions from biomass to ensure they are separated in the facility-level reported data and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data

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[49] See <https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[50]

An ongoing planned improvement is to develop improved estimates of domestic waterborne fuel consumption. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates will continue to be investigated.

EPA is also evaluating the methods used to adjust for conversion of fuels and exports of CO_2. EPA is exploring the approach used to account for CO_2 transport, injection, and geologic storage, as part of this there may be changes made to accounting for CO_2 exports. EPA is also exploring the data provided by EIA in terms of tracking supplemental natural gas which may impact the treatment of adjustments for synthetic fuels.

CH_4 and N_2O from Stationary Combustion

Methodology

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The activity data and emission factors used are described in the following subsections.

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O emission estimates, consumption data for each fuel were obtained from EIA's *Monthly Energy Review* (EIA 2020a). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2020b).[51] Fuel consumption for the industrial sector was adjusted to subtract out mobile source construction and agricultural use, which is reported under mobile sources. Construction and agricultural mobile source fuel use was obtained from EPA (2019) and FHWA (1996 through 2019). Estimates for wood biomass consumption for fuel combustion do not include municipal solid waste, tires, etc., that are reported as biomass by EIA. Non-CO_2 emissions from combustion of the biogenic portion of municipal solid waste and tires is included under waste incineration (Section 3.2). Estimates for natural gas combustion do not include biogas, and therefore non-CO_2 emissions from biogas are not included (see the Planned Improvements section, below). Tier 1 default emission factors for the industrial, commercial, and residential end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

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[50] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[51] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric power sector by control-technology type was based on EPA's Acid Rain Program Dataset (EPA 2021). Total fuel consumption in the electric power sector from EIA (2020a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2020a) data. The combustion technology and fuel use data by facility obtained from EPA (2020a) were only available from 1996 to 2019, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2020a) to the total EIA (2020a) consumption for each year from 1990 to 1995.

Emissions were estimated by multiplying fossil fuel and wood consumption by technology-, fuel-, and country-specific Tier 2 emission factors. The Tier 2 emission factors used are based in part on emission factors published by EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for coal wall-fired boilers, residual fuel oil, diesel oil and wood boilers, natural gas-fired turbines, and combined cycle natural gas units.[52]

Uncertainty and Time-Series Consistency

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[53] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[54] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-18. Stationary combustion CH_4 emissions in 2019 (including biomass) were estimated to be between 5.5 and 20.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 36 percent below to 133 percent above the 2019 emission

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[52] Several of the U.S. Tier 2 emission factors were used in IPCC (2006) as Tier 1 emission factors. See Table A-75 in Annex 3.1 for emission factors by technology type and fuel type for the electric power sector.

[53] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[54] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

estimate of 8.7 MMT CO_2 Eq.[55] Stationary combustion N_2O emissions in 2019 (including biomass) were estimated to be between 18.7 and 37.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 25 percent below to 51 percent above the 2019 emission estimate of 24.9 MMT CO_2 Eq.

Table 3-18: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH₄	8.7	5.5	20.2	-36%	+133%
Stationary Combustion	N₂O	24.9	18.7	37.7	-25%	+51%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019 as discussed below. Details on the emission trends through time are described in more detail in the Methodology section, above. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in Territories, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the non-CO_2 emission estimates from stationary combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the greenhouse gas precursors from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

Methane and N_2O emissions from stationary sources (excluding CO_2) across the entire time series were revised due to revised data from EIA (2020a) and EPA (2020a) relative to the previous Inventory. Most notably, newly published U.S. Territories data from EIA (2020b) was integrated, which impacted coal, fuel oil, and natural gas estimates for U.S. Territories across the time series. EIA (2020a) revised approximate heat rates for electricity and the heat content of electricity for natural gas and noncombustible renewable energy, which impacted electric power energy consumption by sector. As a result of revised natural gas heat contents, EIA updated natural gas consumption in the residential, commercial, and industrial sectors for 2018.

EIA also revised sector allocations for distillate fuel oil, residual fuel oil, and kerosene for 2018, and for propane for 2010 through 2012, 2014, 2017, and 2018, which impacted LPG by sector. EPA (2020a) revised coal, fuel oil, natural gas, and wood consumption statistics for 2018 in the electric power sector. EPA revised distillate fuel oil

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[55] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

carbon contents and LPG heat contents and carbon contents, which affect petroleum consumption in the residential, commercial, and industrial sectors (EPA 2020; ICF 2020). The historical data changes and methodology updates resulted in an average annual decrease of less than 0.05 MMT CO_2 Eq. (0.2 percent) in CH_4 emissions, and an average annual decrease of less than 0.05 MMT CO_2 Eq. (0.1 percent) in N_2O emissions for the 1990 through 2018 period.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated because it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Other forms of biomass-based gas consumption include biogas. EPA will examine EIA and GHGRP data on biogas collected and burned for energy use and determine if CH_4 and N_2O emissions from biogas can be included in future inventories. EIA (2020a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

CH_4 and N_2O from Mobile Combustion

Methodology

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used in the calculations are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle and fuel type.[56]

CH_4 and N_2O emissions factors for newer (starting with model year 2004) on-road gasoline vehicles were calculated by Browning (2019) from annual vehicle certification data compiled by EPA. CH_4 and N_2O emissions factors for older (model year 2003 and earlier) on-road gasoline vehicles were developed by ICF (2004). These emission factors were derived from EPA, California Air Resources Board (CARB) and Environment and Climate Change Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment and Climate Change Canada tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot

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[56] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of driving segment 2 tests were used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were then recombined to approximate average driving characteristics, based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts gram per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions.[57]

Diesel on-road vehicle emission factors were developed by ICF (2006a). CH_4 and N_2O emissions factors for newer (starting at model year 2007) on-road diesel vehicles (those using engine aftertreatment systems) were calculated from annual vehicle certification data compiled by EPA.

CH_4 and N_2O emission factors for AFVs were developed based on the 2019 Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (ANL 2020). For light-duty trucks, EPA used a curve fit of 1999 through 2011 travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2). For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For heavy-duty vehicles, EPA used emission factors for long-haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operations only (tank-to-wheels); upstream well-to-tank emissions are calculated elsewhere in the Inventory. Biodiesel CH_4 emission factors were corrected from GREET values to be the same as CH_4 emission factors for diesel vehicles. GREET overestimated biodiesel CH_4 emission factors based upon an incorrect CH_4-to-THC ratio for diesel vehicles with aftertreatment technology.

Annual VMT data for 1990 through 2019 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2019).[58] VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2018) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2019). VMT for AFVs were estimated based on Browning (2017 and 2018a). The age distributions of the U.S. vehicle fleet were obtained from EPA (2019a, 2000), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2019a).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2019a, 2020c, 2000, 1998, and 1997) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999a) and IPCC (2006) sources.

Non-Road Mobile Sources

The non-road mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives and off-road sources (e.g., construction or agricultural equipment). For non-road sources, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach, for locomotives, aircraft, ships and boats. The Tier 2 approach would require separate fuel-based emissions factors by technology for which data are not available. For

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[57] Additional information regarding the MOBILE model can be found online at <https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model>.

[58] The source of VMT data is FHWA Highway Statistics Table VM-1. In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2019 time period. This resulted in large changes in VMT by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in the current Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

some of the non-road categories, 2-stroke and 4-stroke technologies are broken out and have separate emission factors; those cases could be considered a Tier 2 approach.

To estimate CH_4 and N_2O emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity, and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[59] Activity data were obtained from AAR (2008 through 2019), APTA (2007 through 2019), RailInc (2014 through 2019), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), DLA Energy (2020), DOC (1991 through 2019), DOE (1993 through 2018), DOT (1991 through 2019), EIA (2002, 2007, 2020a), EIA (2020f), EIA (1991 through 2019), EPA (2019a), Esser (2003 through 2004), FAA (2021), FHWA (1996 through 2019),[60] Gaffney (2007), and Whorton (2006 through 2014). Emission factors for non-road modes were taken from IPCC (2006) and Browning (2020 and 2018b).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, using @RISK software. The uncertainty analysis was performed on 2019 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched because emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.9 – Uncertainty Analysis of Emission Estimates. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Based on the uncertainty analysis, mobile combustion CH_4 emissions from all mobile sources in 2019 were estimated to be between 2.3 and 3.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 46 percent above the corresponding 2019 emission estimate of 2.4 MMT CO_2 Eq. Mobile combustion N_2O emissions from mobile sources in 2019 were estimated to be between 16.4 and 21.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 9 percent below to 19 percent above the corresponding 2019 emission estimate of 18.0 MMT CO_2 Eq.

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[59] The consumption of international bunker fuels is not included in these activity data, but emissions related to the consumption of international bunker fuels are estimated separately under the International Bunker Fuels source category.

[60] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES model gasoline volumes to estimate non-road mobile source CH_4 and N_2O emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both non-road trucks and equipment. For construction and commercial/industrial category gasoline estimates, the 2014 and older MF-24 volumes represented non-road trucks only; therefore, the MOVES gasoline volumes for construction and commercial/industrial categories are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES equipment gasoline volumes in the construction and commercial/industrial categories.

Table 3-19: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Mobile Sources (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate[a] (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO₂ Eq.)		(Percent)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH₄	2.4	2.3	3.5	-2%	+46%
Mobile Sources	N₂O	18.0	16.4	21.3	-9%	+19%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty estimation methodology. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH₄ and N₂O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH₄ and N₂O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the emission estimates from mobile combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

Updates were made to CH₄ and N₂O emission factors for newer non-road gasoline and diesel vehicles. Previously, these emission factors were calculated using the updated 2006 IPCC Tier 3 guidance and the nonroad component EPA's MOVES2014b model. CH₄ emission factors were calculated directly from MOVES. N₂O emission factors were calculated using MOVES-Nonroad activity and emission factors in g/kWh by fuel type from the European Environment Agency. Updated emission factors were developed this year using EPA engine certification data for non-road small and large spark-ignition (SI) gasoline engines and compression-ignition diesel engines (model year 2011 and newer), as well as non-road motorcycles (model year 2006 and newer), SI marine engines (model year 2011 and newer), and diesel marine engines (model year 2000 and newer).

The collective result of these changes was a net decrease in CH₄ emissions and an increase in N₂O emissions from mobile combustion relative to the previous Inventory. Methane emissions decreased by 23.2 percent. Nitrous oxide emissions increased by 23.6 percent.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019 with one recent notable exception. An update by FHWA to the method for estimating on-road VMT created an inconsistency in on-road CH₄ and N₂O for the time periods 1990 to 2006 and 2007 to 2019. Details on the emission trends and methodological inconsistencies through time are described in the Methodology section above.

Planned Improvements

While the data used for this report represent the most accurate information available, several areas for improvement have been identified.

- Update emission factors for motorcycles. The Inventory does not currently account for advanced technology motorcycles. EPA certification data can be used to update motorcycle assumptions to better capture the portion of the motorcycle fleet using advanced emissions controls.

- Update emission factors for buses. The Inventory currently groups buses into the heavy-duty vehicle category. New emission factors specific to buses can be developed from EPA certification data.

- Update emission factors for ships and boats using residual fuel and distillate fuel, emission factors for locomotives using ultra low sulfur diesel, and emission factors for aircraft using jet fuel. The Inventory is currently using IPCC default values for these emissions factors.

- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. Since 2015, all ships travelling within 200 nautical miles of the US coastlines must use distillate fuels thereby overestimating the residual fuel used by US vessels and underestimating distillate fuel use in these ships.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRF Source Category 1A)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEU) in the United States. The fuels used for these purposes are diverse, including natural gas, hydrocarbon gas liquids (HGL),[61] asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy use of lubricants, paraffin waxes, bitumen / asphalt, and solvents are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-5). In addition, estimates of non-energy use emissions included here do not include emissions already reflected in the IPPU sector, e.g., fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are reduced to account for these emissions already included under IPPU.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series

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[61] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, and pentanes plus, and HGLs include olefins, such as ethylene, propylene, and butylene. Adjustments were made in the current Inventory report to HGL activity data, carbon content coefficients, and heat contents HGL. For more information about the updated HGL data and assumptions, see the Recalculations Discussion section below.

and across all uses, about 62 percent of the total C consumed for non-energy purposes was stored in products (e.g., plastics), and not released to the atmosphere; the remaining 38 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this Inventory. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. There are also net exports of petrochemical intermediate products that are not completely accounted for in the EIA data, and the Inventory calculations adjust for the effect of net exports on the mass of C in non-energy applications.

As shown in Table 3-20, fossil fuel emissions in 2019 from the non-energy uses of fossil fuels were 128.8 MMT CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2019, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,635.0 TBtu (see Table 3-21). A portion of the C in the 5,635.0 TBtu of fuels was stored (228.8 MMT CO_2 Eq.), while the remaining portion was emitted (128.8 MMT CO_2 Eq.). Non-energy use emissions decreased by 0.7 percent from 2018 to 2019 mainly due to a decrease in the ratio between C stored and potential emissions. See Annex 2.3 for more details.

Table 3-20: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent)

Year	1990		2005		2015	2016	2017	2018	2019
Potential Emissions	306.1		367.4		322.8	317.8	332.7	352.8	357.5
C Stored	193.3		238.3		214.4	218.0	219.2	223.1	228.8
Emissions as a % of Potential	37%		35%		34%	31%	34%	37%	36%
C Emitted	**112.8**		**129.1**		**108.5**	**99.8**	**113.5**	**129.7**	**128.8**

Methodology

The first step in estimating C stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The C content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific C content values. Both the non-energy fuel consumption and C content data were supplied by the EIA (2020) (see Annex 2.1). Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-21 and Table 3-22 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[62] Consumption of natural gas, HGL, pentanes plus, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values were also adjusted to subtract net exports of HGL components (e.g., propylene, ethane).

For the remaining non-energy uses, the quantity of C stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, HGL, pentanes plus, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on C stocks and flows were used to develop C storage factors, calculated as the ratio of (a) the C stored by the fuel's non-energy products to (b) the total C content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.

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[62] These source categories include Iron and Steel Production, Lead Production, Zinc Production, Ammonia Manufacture, Carbon Black Manufacture (included in Petrochemical Production), Titanium Dioxide Production, Ferroalloy Production, Silicon Carbide Production, and Aluminum Production.

- For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of C in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

Table 3-21: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2015	2016	2017	2018	2019
Industry	**4,317.2**	**5,111.1**	**4,864.5**	**4,833.1**	**5,089.6**	**5,445.4**	**5,492.3**
Industrial Coking Coal	NO	80.4	122.4	89.6	113.0	124.8	132.1
Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants	282.4	260.9	418.9	496.4	588.0	675.9	664.6
Asphalt & Road Oil	1,170.2	1,323.2	831.7	853.4	849.2	792.8	843.9
HGL	1,218.4	1,610.4	2,160.2	2,128.0	2,193.5	2,505.1	2,545.1
Lubricants	186.3	160.2	142.1	135.1	124.9	121.9	117.6
Pentanes Plus	117.5	95.4	78.3	53.1	81.7	105.2	154.7
Naphtha (<401 °F)	327.0	679.5	418.1	398.2	413.0	421.0	368.8
Other Oil (>401 °F)	663.6	499.5	216.9	204.6	242.9	219.0	211.7
Still Gas	36.7	67.7	162.2	166.1	163.8	166.9	158.7
Petroleum Coke	28.1	106.2	NO	NO	NO	NO	NO
Special Naphtha	101.1	60.9	97.1	89.0	95.3	87.0	89.3
Distillate Fuel Oil	7.0	11.7	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.4	12.8	10.2	12.4	10.4
Miscellaneous Products	137.8	112.8	188.9	191.3	198.8	198.0	180.2
Transportation	**176.0**	**151.3**	**162.8**	**154.4**	**142.0**	**137.0**	**132.1**
Lubricants	176.0	151.3	162.8	154.4	142.0	137.0	132.1
U.S. Territories	**50.8**	**114.9**	**10.3**	**10.5**	**10.7**	**10.7**	**10.7**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	9.3	9.5	9.6	9.6	9.6
Total	**4,544.0**	**5,377.3**	**5,037.7**	**4,998.0**	**5,242.3**	**5,593.0**	**5,635.0**

NO (Not Occurring)

Table 3-22: 2019 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO$_2$ Eq.)
Industry	**5,492.3**	**NA**	**94.6**	**NA**	**62.1**	**32.5**	**119.2**
Industrial Coking Coal	132.1	25.59	3.4	0.10	0.3	3.0	11.2
Industrial Other Coal	9.5	26.07	0.2	0.62	0.2	0.1	0.3
Natural Gas to Chemical Plants	664.6	14.47	9.6	0.62	5.9	3.6	13.4
Asphalt & Road Oil	843.9	20.55	17.3	1.00	17.3	0.1	0.3
HGL	2,545.1	16.85	42.9	0.62	26.6	16.3	59.8
Lubricants	117.6	20.20	2.4	0.09	0.2	2.2	7.9
Pentanes Plus	154.7	18.24	2.8	0.62	1.7	1.1	3.9
Naphtha (<401° F)	368.8	18.55	6.8	0.62	4.2	2.6	9.5
Other Oil (>401° F)	211.7	20.17	4.3	0.62	2.6	1.6	6.0
Still Gas	158.7	17.51	2.8	0.62	1.7	1.1	3.9
Petroleum Coke	NO	27.85	NO	0.30	NO	NO	NO

Special Naphtha	89.3	19.74	1.8	0.62	1.1	0.7	2.5
Distillate Fuel Oil	5.8	20.22	0.1	0.50	0.1	0.1	0.2
Waxes	10.4	19.80	0.2	0.58	0.1	0.1	0.3
Miscellaneous Products	180.2	0.00	0.0	0.00	0.0	0.0	0.0
Transportation	**132.1**	**NA**	**2.7**	**NA**	**0.2**	**2.4**	**8.9**
Lubricants	132.1	20.20	2.7	0.09	0.2	2.4	8.9
U.S. Territories	**10.7**	**NA**	**0.2**	**NA**	**+**	**0.2**	**0.7**
Lubricants	1.0	20.20	+	0.09	+	+	0.1
Other Petroleum (Misc. Prod.)	9.6	20.00	0.2	0.10	+	0.2	0.6
Total	**5,635.0**		**97.5**		**62.4**	**35.1**	**128.8**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 TBtu, MMT C, or MMT CO_2 Eq.

NA (Not Applicable)

NO (Not Occurring)

[a] To avoid double counting, net exports have been deducted.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-20). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery (waste gas from chemicals), Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data* (EPA 2020), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015, 2016b, 2018b, 2021), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2014b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017, 2021); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014); Bank of Canada (2012, 2013, 2014, 2016, 2017, 2018, 2019, 2020); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (1990 through 2018); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013, 2014a, 2016a, 2018a, 2019); the Rubber Manufacturers' Association (RMA 2009, 2011, 2014, 2016, 2018); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013); the Independent Chemical Information Service (ICIS 2008, 2016); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020b); and the *Guide to the Business of Chemistry* (ACC 2020a). Specific data sources are listed in full detail in Annex 2.3.

Box 3-5: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[63] In this Inventory, C storage and C emissions from product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon

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[63] See for example Volume 3: Industrial Processes and Product Use, and Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Emitted from Non-Energy Uses of Fossil Fuels source category (CRF Source Category 1A5).[64]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. Although emissions from these non-energy uses are reported in the Energy chapter the methodologies used to determine emissions are compatible with the 2006 IPCC Guidelines. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., C inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Table 3-22).

For those inputs, U.S. country-specific data on C stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the C stored by the fossil fuel non-energy products to the total C content of the fuel consumed, taking into account losses in the production process and during product use.[65] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a C balance calculation, breaking out the C emissions from non-energy use of lubricants, waxes, and asphalt and road oil. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance and to avoid double counting. Due to U.S. national circumstances, reporting these C emissions separately under IPPU would involve making artificial adjustments to allocate both the C inputs and C outputs of the non-energy use C balance. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting these non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use C carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. To avoid presenting an incomplete C balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of C storage and C emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the C storage and C emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, emissions from non-energy uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

Uncertainty and Time-Series Consistency

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo Stochastic Simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, HGL, pentanes plus, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2)

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[64] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

[65] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-21 and Table 3-22), the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-23 (emissions) and Table 3-24 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2019 was estimated to be between 81.0 and 187.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 37 percent below to 45 percent above the 2019 emission estimate of 128.8 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	99.3	56.4	160.4	-43%	+62%
Asphalt	CO_2	0.3	0.1	0.6	-58%	+118%
Lubricants	CO_2	16.9	14.0	19.6	-17%	+16%
Waxes	CO_2	0.3	0.2	0.6	-24%	+90%
Other	CO_2	12.0	2.5	13.9	-79%	+16%
Total	**CO_2**	**128.8**	**81.0**	**187.2**	**-37%**	**+45%**

Note: Totals may not sum due to independent rounding.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Table 3-24: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2019 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a]			
			(%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	62.0%	49.5%	72.8%	-20%	+18%
Asphalt	CO_2	99.6%	99.1%	99.8%	-0.5%	+0.2%
Lubricants	CO_2	9.2%	3.9%	17.5%	-58%	+91%
Waxes	CO_2	57.8%	47.5%	67.5%	-18%	+17%
Other	CO_2	11.3%	7.9%	81.0%	-30%	+618%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-24, feedstocks and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows— appears to have tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current

analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019 as discussed below. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

In order to ensure the quality of the emission estimates from non-energy uses of fossil fuels, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of C (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2018 totals as well as their trends across the time series.

Some degree of double counting may occur between these estimates of non-energy use of fuels and process emissions from petrochemical production presented in the Industrial Processes and Produce Use (IPPU) sector. This was examined and is not considered to be a significant issue since the non-energy use industrial release data includes different categories of sources than those included in the IPPU sector. Data integration is not feasible at this time as feedstock data from EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries (e.g., petrochemical production) as currently collected through EPA's GHGRP and used for the petrochemical production category.

Recalculations Discussion

The "miscellaneous products" category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. The EIA does not have firm data concerning the amounts of various products that are being reported in the "miscellaneous products" category; however, EIA has indicated that recovered sulfur compounds from petroleum and natural gas processing, and potentially also carbon black feedstock could be reported in this category. Recovered sulfur has no carbon content and would not be reported in the NEU calculation or elsewhere in the Inventory. Based on this information, the miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was updated to be zero across the time series.

In addition, adjustments were made to activity data, carbon content coefficients, and heat contents for HGL for 1990 to 2018. Historical HGL activity data from 1990 to 2007 were adjusted to use EIA's Petroleum Supply Annual tables for consistency with the rest of the entire time series (i.e., 2008 to 2019). In previous Inventory reports, HGL activity data from 1990 to 2007 were extracted from the American Petroleum Institute's *Sales of Natural Gas Liquids and Liquefied Refinery Gases*. Thus, the HGL data source for the 1990 to 2007 portion of the time series was updated to align with the HGL activity data used for 2008 to 2019 as well as with data used in other Energy sector source categories (e.g., EIA's *Monthly Energy Review* (EIA 2020a)). In addition, the HGL carbon content coefficient

for NEU was updated by separating each fuel out by its natural gas liquid (NGL)[66] and associated olefin to calculate a more accurate and annually variable factor, and the heat contents for HGL and pentanes plus were updated using updated data from EIA's *Monthly Energy Review* (EIA 2020a).

Natural Gas to Chemical Plants data were updated to reflect the 2018 MECS data. This resulted in an increase in natural gas used for NEU of 120 percent in 2018 compared to previous reports. Adjustments were also made to historical calculations to linearly interpolate between EIA's MECS data years. Previously, fuel consumption data for years between MECS releases were assumed to be equal to the previous year of data.

Non-energy use of petroleum coke consumption was adjusted to account for leap years when converting from barrels per day to barrels per year. The carbon factor used to determine the amount of petroleum coke used in several IPPU categories was updated to be consistent with the factors used in the fossil fuel combustion estimates. This update impacted the amount of petroleum coke subtracted from non-energy use calculations.

Overall, these changes resulted in an average annual decrease of 10.9 MMT CO_2 Eq. (8.7 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2018, relative to the previous Inventory. This decrease is primarily due to the removal of miscellaneous products, which previously constituted an average of 8.2 percent of total emissions from 1990 to 2018.

Planned Improvements

There are several future improvements planned:

- More accurate accounting of C in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the C mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued as part of quality control procedures. First, accounting of C in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down C input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up C output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil C. Additional fates may be researched, including the fossil C load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).
- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum. A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- Updating the average C content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on C emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive C in solvents. Additional sources of solvents data will be investigated in order to update the C content assumptions.
- Updating the average C content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data sources may facilitate updating the average C content for this category.
- Revising the methodology for consumption, production, and C content of plastics was researched;

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[66] NGL are defined by EIA as "a group of hydrocarbons including ethane, propane, normal butane, isobutane, and natural gasoline. [NGL] generally include natural gas plant liquids and all liquefied refinery gases except olefins" (EIA 2020b).

because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.

- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing C fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the Inventory; in particular, the carbon black abraded and stored in tires.

3.3 Incineration of Waste (CRF Source Category 1A5)

Incineration is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; EPA 2020; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, incineration of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Incineration of waste results in conversion of the organic inputs to CO_2. According to the *2006 IPCC Guidelines*, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste incineration are calculated by estimating the quantity of waste combusted and the fraction of the waste that is C derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net C flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components of MSW and scrap tires—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a "non-hazardous" waste and are included in the waste incineration estimate, though waste disposal practices for tires differ from MSW. Estimates on emissions from hazardous waste incineration can be found in Annex 2.3 and are accounted for as part of the C mass balance for non-energy uses of fossil fuels.

Approximately 20.8 million metric tons of MSW were incinerated in 2011 (van Haaren et al. 2010). Updated data were not available for 2012 through 2019 from this source so the data were proxied to the 2011 estimate. Carbon dioxide emissions from incineration of waste increased 42 percent since 1990, to an estimated 11.5 MMT CO_2 (11,471 kt) in 2019, as the volume of scrap tires and other fossil C-containing materials in waste increased (see Table 3-25 and Table 3-26).

Waste incineration is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the incineration of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.05 kt CH_4) in 2019 and have decreased by 11 percent since 1990. Nitrous oxide emissions from the incineration of waste were estimated to be 0.3 MMT CO_2 Eq. (1 kt N_2O) in 2019 and have decreased by 32 percent since 1990. This decrease is driven by the decrease in total MSW incinerated.

Table 3-25: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (MMT CO_2 Eq.)

Gas/Waste Product	1990	2005	2015	2016	2017	2018	2019
CO_2	**8.1**	**12.7**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**
Plastics	5.7	7.2	6.3	6.4	6.5	6.6	6.6
Synthetic Rubber in Tires	0.3	1.6	1.4	1.4	1.3	1.3	1.2
Carbon Black in Tires	0.4	2.0	1.8	1.7	1.5	1.5	1.5
Synthetic Rubber in MSW	0.9	0.8	0.7	0.7	0.7	0.7	0.7
Synthetic Fibers	0.8	1.2	1.3	1.4	1.4	1.4	1.4
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O	**0.5**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**8.5**	**13.1**	**11.8**	**11.8**	**11.8**	**11.9**	**11.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 3-26: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (kt)

Gas/Waste Product	1990	2005	2015	2016	2017	2018	2019
CO_2	**8,062**	**12,713**	**11,533**	**11,525**	**11,537**	**11,547**	**11,471**
Plastics	5,699	7,163	6,316	6,370	6,532	6,588	6,588
Synthetic Rubber in Tires	308	1,599	1,440	1,369	1,298	1,264	1,229
Carbon Black in Tires	385	1,958	1,755	1,670	1,585	1,544	1,503
Synthetic Rubber in MSW	854	766	703	717	731	739	739
Synthetic Fibers	816	1,227	1,319	1,399	1,392	1,412	1,410
CH_4	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O	**2**	**1**	**1**	**1**	**1**	**1**	**1**

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic fibers, and synthetic rubber in MSW, as well as the incineration of synthetic rubber and carbon black in scrap tires. The emission estimates are calculated for all four sources on a mass-basis based on the data available. These emissions were estimated by multiplying the mass of each material incinerated by the C content of the material and the fraction oxidized (98 percent). Plastics incinerated in MSW were categorized into seven plastic resin types, each material having a discrete C content. Similarly, synthetic rubber is categorized into three product types, and synthetic fibers were categorized into four product types, each having a discrete C content. Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. More detail on the methodology for calculating emissions from each of these waste incineration sources is provided in Annex 3.7.

For each of the methods used to calculate CO_2 emissions from the incineration of waste, data on the quantity of product combusted and the C content of the product are needed. For plastics, synthetic rubber, and synthetic fibers in MSW, the amount of specific materials discarded as MSW (i.e., the quantity generated minus the quantity recycled) was taken from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* (EPA 2000 through 2003, 2005 through 2014), and *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015; EPA 2016; EPA 2018a; EPA 2019; EPA 2020) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For 2012 through 2019 data on total waste incinerated were assumed to equal to the 2011 value from Shin (2014). For synthetic rubber and carbon black in scrap tires, information was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2019 data (RMA 2020). Average C contents for the "Other" plastics category and synthetic rubber in MSW were calculated from 1998 and 2002 production statistics; C content for 1990 through 1998 is based on the 1998 value; C content for 1999 through

2001 is the average of 1998 and 2002 values; and C content for 2002 through 2019 is based on the 2002 value. Carbon content for synthetic fibers was calculated from a weighted average of production statistics from 1990 through 2019. Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (RMA 2012a). The mass of incinerated material is multiplied by its C content to calculate the total amount of carbon stored.

The assumption that 98 percent of organic C is oxidized (which applies to all waste incineration categories for CO_2 emissions) was reported in EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006). This percentage is multiplied by the carbon stored to estimate the amount of carbon emitted.

Incineration of waste, including MSW, also results in emissions of CH_4 and N_2O. These emissions were calculated as a function of the total estimated mass of waste incinerated and emission factors. As noted above, CH_4 and N_2O emissions are a function of total waste incinerated in each year; for 1990 through 2008, these data were derived from the information published in *BioCycle* (van Haaren et al. 2010). Data for 2009 and 2010 were interpolated between 2008 and 2011 values. Data for 2011 were derived from Shin (2014). Data on total waste incinerated was not available in the *BioCycle* data set for 2012 through 2019, so these values were assumed to equal the 2011 *BioCycle* dataset value.

Table 3-27 provides data on MSW discarded and percentage combusted for the total waste stream. The emission factors of N_2O and CH_4 emissions per quantity of MSW combusted are default emission factors for the default continuously-fed stoker unit MSW incineration technology type and were taken from IPCC (2006).

Table 3-27: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted (BioCycle dataset)

Year	Waste Discarded	Waste Incinerated	Incinerated (% of Discards)
1990	235,733,657	30,632,057	13.0%
2005	259,559,787	25,973,520	10.0%
2015	273,116,704[a]	20,756,870	7.6%
2016	273,116,704[a]	20,756,870	7.6%
2017	273,116,704[a]	20,756,870	7.6%
2018	273,116,704[a]	20,756,870	7.6%
2019	273,116,704[a]	20,756,870	7.6%

[a] Assumed equal to 2011 value.
Source: van Haaren et al. (2010), Shin (2014).

Uncertainty and Time-Series Consistency

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the Inventory estimate. Uncertainty estimates and distributions for waste generation variables (i.e., plastics, synthetic rubber, and textiles generation) were obtained through a conversation with one of the authors of the Municipal Solid Waste in the United States reports. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the other variables; thus, uncertainty estimates for these variables were determined using

assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW incineration rate; fraction oxidized; missing data on waste composition; average C content of waste components; assumptions on the synthetic/biogenic C ratio; and combustion conditions affecting N_2O emissions. The highest levels of uncertainty surround the variables that are based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-28. Waste incineration CO_2 emissions in 2019 were estimated to be between 8.6 and 14.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 25 percent below to 27 percent above the 2019 emission estimate of 11.5 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2019 were estimated to be between 0.2 and 1.3 MMT CO_2 Eq. This indicates a range of 50 percent below to 325 percent above the 2019 emission estimate of 0.3 MMT CO_2 Eq.

Table 3-28: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	11.5	8.6	14.5	-25%	27%
Incineration of Waste	N_2O	0.3	0.2	1.3	-50%	325%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates from waste incineration, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from incineration of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors in the use of activity data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

The waste incineration estimates have recently relied on MSW mass flow (i.e., tonnage) data that has not been updated since 2011. These values come from *BioCycle* (Shin 2014) and *EPA Facts and Figures* (EPA 2015). EPA performed an examination of facility-level MSW tonnage data availability, primarily focusing on EPA's GHGRP data, Energy Information Administration (EIA) waste-to-energy data, and other sources. EPA concluded that the MSW mass flow of waste incinerated can be derived from GHGRP data and that the GHGRP dataset is the most complete dataset (i.e., includes the most facilities), but does not contain data for all inventory years (1990 through 2010). The EIA data can be used to supplement years not available in the GHGRP dataset and corroborate MSW mass flow

tonnage obtained for years in which GHGRP data are available. These MSW mass flow tonnages currently influence calculations for CO_2 and non-CO_2 emissions.

Additional improvements will focus on investigating new methods and sources for CO_2 emission estimates. As part of the Public Review process of this year's Inventory cycle, EPA proposed a new method for calculating emissions associated with waste incineration. The proposed method relied on MSW tonnage estimates back calculated from GHGRP reporting data and MSW assumed carbon content factors based on the EPA's Facts and Figures Reports. Based on review and discussions with industry representatives it was felt that the proposed approach could lead to an overestimate of fossil carbon content of waste combusted. Therefore, the approach used here reverts to the existing methodology used in past calculations.

Future, proposed improvements to the current CO_2 emissions estimation methodology build off the work done for the proposed approach and include the calculation of an overall carbon content for MSW incinerated. GHGRP and EIA both provide emissions information for CO_2, which will allow EPA to calculate an overall carbon content of MSW incinerated and apply this to MSW mass flows. Further research is required to compare the carbon contents of MSW incinerated from GHGRP and EIA.

Currently, emission estimates for the biomass and biomass-based fuels source category included in this Inventory are limited to woody biomass, ethanol, and biodiesel. EPA will incorporate emissions from biogenic components of MSW to biomass and biomass-based fuels or waste incineration in future Inventory assessments.

3.4 Coal Mining (CRF Source Category 1B1a)

Three types of coal mining-related activities release CH_4 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of CH_4 emissions (see Table 3-30 and Table 3-31) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2019, 226 underground coal mines and 432 surface mines were operating in the United States (EIA 2020). In recent years, the total number of active coal mines in the United States has declined. In 2019, the United States was the third-largest coal producer in the world (640 MMT), after China (3,693 MMT) and India (769 MMT) (IEA 2020).

Table 3-29: Coal Production (kt)

Year	Underground		Surface		Total	
	Number of Mines	Production	Number of Mines	Production	Number of Mines	Production
1990	1,683	384,244	1,656	546,808	3,339	931,052
2005	586	334,399	789	691,447	1,398	1,025,846
2015	305	278,344	529	534,092	834	812,435
2016	251	228,707	439	431,282	690	659,989
2017	237	247,778	434	454,301	671	702,080
2018	236	249,804	430	435,521	666	685,325
2019	226	242,557	432	397,750	658	640,307

Underground mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. Methane emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and

depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2019 were estimated to be 1,895 kt (47.4 MMT CO_2 Eq.), a decline of approximately 51 percent since 1990 (see Table 3-30 and Table 3-31). In 2019, underground mines accounted for approximately 73 percent of total emissions, surface mines accounted for 13 percent, and post-mining activities accounted for 14 percent. In 2019, total CH_4 emissions from coal mining decreased by approximately 10 percent relative to the previous year. This decrease was due to a decrease in annual coal production and a decrease in reported annual ventilation emissions.[67] The amount of CH_4 recovered and used in 2019 decreased by approximately 17 percent compared to 2018 levels. In 2019, all but two mines reported lower levels of CH_4 recovered and used compared to 2018 levels.

Table 3-30: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Underground (UG) Mining	**74.2**		**42.0**		**44.9**	**40.7**	**40.7**	**38.9**	**34.5**
Liberated	80.8		59.7		61.2	57.1	58.1	57.7	50.1
Recovered & Used	(6.6)		(17.7)		(16.4)	(16.4)	(17.4)	(18.8)	(15.7)
Surface Mining	**10.8**		**11.9**		**8.7**	**6.8**	**7.2**	**7.0**	**6.4**
Post-Mining (UG)	**9.2**		**7.6**		**5.8**	**4.8**	**5.3**	**5.3**	**5.2**
Post-Mining (Surface)	**2.3**		**2.6**		**1.9**	**1.5**	**1.6**	**1.5**	**1.4**
Total	**96.5**		**64.1**		**61.2**	**53.8**	**54.8**	**52.7**	**47.4**

Table 3-31: CH_4 Emissions from Coal Mining (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Underground (UG) Mining	**2,968**		**1,682**		**1,796**	**1,629**	**1,626**	**1,556**	**1,379**
Liberated	3,231		2,388		2,450	2,283	2,324	2,307	2,005
Recovered & Used	(263)		(706)		(654)	(654)	(698)	(751)	(627)
Surface Mining	**430**		**475**		**347**	**273**	**290**	**280**	**255**
Post-Mining (UG)	**368**		**306**		**231**	**193**	**213**	**212**	**206**
Post-Mining (Surface)	**93**		**103**		**75**	**59**	**63**	**61**	**55**
Total	**3,860**		**2,565**		**2,449**	**2,154**	**2,191**	**2,109**	**1,895**

Methodology

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground coal mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for both coal production from underground mines and surface mines). The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate CH_4 emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from

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[67] This indicates lower underground mine activity, which is supported by EIA coal production data for 2019 (reduction in production compared to 2018 and 2017).

surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and use the liberated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[68] (Subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA) (MSHA 2020), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2020).[69] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; they have the option of recording and reporting their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[70]

Since 2013, ventilation CH_4 emission estimates have been calculated based on both quarterly GHGRP data submitted by underground mines and on quarterly measurement data obtained directly from MSHA. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data. For GHGRP data, reported quarterly ventilation methane emissions (metric tons) are summed for each mine to develop mine-specific annual ventilation emissions. For MSHA data, the average daily CH_4 emission rate for each mine is determined using the CH_4 total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH_4 emission rate is then multiplied by 365 days to estimate annual ventilation CH_4 emissions for the MSHA dataset.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Nineteen mines used degasification systems in 2019 and 17 of these mines reported the CH_4 removed through these systems to EPA's GHGRP under Subpart FF (EPA 2020). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine are added to estimate the CH_4 liberated from degasification systems. Thirteen of the 19 mines with degasification systems had operational CH_4 recovery and use projects (see step 1.3 below).[71]

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[68] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[69] Underground coal mines report to EPA under Subpart FF of the GHGRP (40 CFR Part 98). In 2019, 65 underground coal mines reported to the program.

[70] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[71] Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 14 of the 19 mines that used degasification systems in 2019. Data from state gas well production databases were used exclusively for two mines and state gas well production data were used to supplement GHGRP degasification data for the remaining three mines (DMME 2020, GSA 2020, and WVGES 2020).

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[72] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF.[73] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the GHGRP (Subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. There were five mines with degasification systems that include pre-mining wells that were mined through in 2019. For three of these mines, GHGRP data were supplemented with historical data from state gas well production databases (GSA 2020 and WVGES 2020), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009; ERG 2020). State gas well production data were exclusively used for the remaining two mines (DMME 2020 and GSA 2020).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Thirteen mines had CH_4 recovery and use projects in place in 2019, including one mine that had two recovery and use projects. Thirteen of these projects involved degasification systems and one involved a ventilation air methane abatement project (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. One mine used recovered CH_4 to heat mine ventilation air (data were unavailable for estimating CH_4 recovery at this mine). One mine destroyed the recovered CH_4 (VAM) using Regenerative Thermal Oxidation (RTO) without energy recovery.

The CH_4 recovered and used (or destroyed) at the twelve mines described above for which data were available are estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from seven of the 12 mines that deployed degasification systems in 2019. Based on weekly measurements, the GHGRP degasification destruction data summaries for each mine are added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to estimate CH_4 recovered and used from the remaining five mines that deployed degasification systems in 2019 (DMME 2020, GSA 2020). These five mines intersected pre-mining wells in 2019. Supplemental information is used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data not reported under Subpart FF of EPA's GHGRP (see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The supplemental data is obtained from state gas production databases as well as mine-specific information on the timing of mined-through pre-mining wells.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2020).

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[72] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

[73] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under Subpart FF of EPA's GHGRP.

Step 2: Estimate CH₄ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH₄ emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2020) is multiplied by basin-specific CH₄ contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH₄ from over- and under-burden) to estimate CH₄ emissions (King 1994, Saghafi 2013). For post-mining activities, basin-specific coal production is multiplied by basin-specific CH₄ contents and a mid-range 32.5 percent emission factor for CH₄ desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data were compiled from AAPG (1984) and USBM (1986).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements used were not continuous but rather quarterly instantaneous readings that were used to determine the average annual emission rates. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH₄ emissions (Mutmansky & Wang 2000). Equipment measurement uncertainty is applied to GHGRP data.

Estimates of CH₄ liberated and recovered by degasification systems are relatively certain for utilized CH₄ because of the availability of EPA's GHGRP data and gas sales information. Many of the liberation and recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the liberated CH₄ and avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH₄ monitoring of mines that report degasification systems, and continuous CH₄ monitoring is required for CH₄ utilized on- or off-site. Since 2012, GHGRP data have been used to estimate CH₄ emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this sub-source. Beginning in 2013, GHGRP data were also used for determining CH₄ recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground emissions constitute the majority of total coal mining emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-32. Coal mining CH₄ emissions in 2019 were estimated to be between 43.2 and 57.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8.8 percent below to 20.3 percent above the 2019 emission estimate of 47.4 MMT CO_2 Eq.

Table 3-32: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Coal Mining (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH₄	47.4	43.2	57.0	-8.8%	+20.3%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for coal mining, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from coal mining. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Emission estimates for coal mining rely in large part on data reported by coal mines to EPA's GHGRP. EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual report. Additional QA/QC and verification procedures occur for each GHGRP subpart.

Recalculations Discussion

State gas sales production values were updated for one mine for 2011 and 2012, and for 1994 to 2018 for another mine, as part of normal updates. These changes resulted in slightly higher degasification CH_4 emissions and CH_4 emissions avoided from underground mining. The change in both the degasification emissions and emissions avoided is less than 0.5 percent over the 1994 to 2018 time series, compared to the previous Inventory.

Annual coal production numbers were updated for 2001 to 2018 based on revised data from EIA. The previously used coal production numbers were revised by EIA, primarily for the Appalachian basins. This update resulted in changes to surface mining and post-surface mining emissions for 2001 to 2018. The change in emissions averaged an increase of approximately 9 percent over the 2001 to 2018 time series. The highest change was in 2007 (11.4 percent) and the lowest change was in 2015 (5.3 percent), compared to the previous Inventory.

Planned Improvements

EPA intends to include estimating fugitive CO_2 emissions from underground and surface mining, based on methods included in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

3.5 Abandoned Underground Coal Mines (CRF Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or, if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 7.2 to 10.8 MMT CO_2 Eq. from 1990 to 2019, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (10.8 MMT CO_2 Eq.) due to the large number of gassy mine[74] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. In 2019 there were no gassy mine closures. Gross abandoned mine emissions decreased slightly from 8.9 MMT CO_2 Eq. (355 kt CH_4) in 2018 to 8.5 (341 kt CH_4) MMT CO_2 Eq. in 2019 (see Table 3-33 and Table 3-34). Gross emissions are reduced by CH_4 recovered and used at 45 mines, resulting in net emissions in 2019 of 5.9 MMT CO_2 Eq.

Table 3-33: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Underground Mines	7.2		8.4		9.0	9.5	9.2	8.9	8.5
Recovered & Used	0.0		(1.8)		(2.6)	(2.8)	(2.7)	(2.7)	(2.6)
Total	**7.2**		**6.6**		**6.4**	**6.7**	**6.4**	**6.2**	**5.9**

Note: Parentheses indicate negative values.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 3-34: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Underground Mines	288		334		359	380	367	355	341
Recovered & Used	0.0		(70)		(102)	(112)	(109)	(107)	(104)
Total	**288**		**264**		**256**	**268**	**257**	**247**	**237**

+ Does not exceed 0.5 kt.

Methodology

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed

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[74] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 mcfd).

for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

In order to estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. A rate-time equation can be generated that can be used to predict future emissions. This decline through time is hyperbolic in nature and can be empirically expressed as:

$$q = q_i (1 + bD_i t)^{(-1/b)}$$

where,

q	=	Gas flow rate at time t in million cubic feet per day (mmcfd)
q_i	=	Initial gas flow rate at time zero (t_o), mmcfd
b	=	The hyperbolic exponent, dimensionless
D_i	=	Initial decline rate, 1/year
t	=	Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability and adsorption isotherms (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. For this analysis of flooded abandoned mines, there was not enough data to establish basin-specific equations, as was done with the vented, non-flooding mines (EPA 2004). This decline through time can be empirically expressed as:

$$q = q_i e^{(-Dt)}$$

where,

q	=	Gas flow rate at time t in mmcfd
q_i	=	Initial gas flow rate at time zero (t_o), mmcfd
D	=	Decline rate, 1/year
t	=	Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 − [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (mcfd) of CH_4 account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that

the 527 abandoned mines closed after 1972 produced CH$_4$ emissions greater than 100 mcfd when active. Further, the status of 304 of the 527 mines (or 58 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or 3) flooded (enough to inhibit CH$_4$ flow to the atmosphere). The remaining 42 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004). Table 3-35 presents the count of mines by post-abandonment state, based on EPA's probability distribution analysis.

Table 3-35: Number of Gassy Abandoned Mines Present in U.S. Basins in 2019, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	42	26	52	120	146	266
Illinois	34	3	14	51	31	82
Northern Appl.	47	22	16	85	39	124
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**151**	**55**	**100**	**306**	**226**	**532**

Inputs to the decline equation require the average CH$_4$ emission rate prior to abandonment and the date of abandonment. Generally, these data are available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH$_4$ emissions from coal mining came from seventeen counties in seven states. Mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the U.S., representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH$_4$ emissions rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH$_4$ ventilation emission rates greater than 100 mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2020). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect only ventilation emissions for pre-1990 closures. CH$_4$ degasification amounts were added to the quantity of CH$_4$ vented to determine the total CH$_4$ liberation rate for all mines that closed between 1992 and 2019. Since the sample of gassy mines described above is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02 to account for all U.S. abandoned mine emissions.

From 1993 through 2019, emission totals were downwardly adjusted to reflect CH$_4$ emissions avoided from those abandoned mines with CH$_4$ recovery and use or destruction systems. The Inventory totals were not adjusted for abandoned mine CH$_4$ emissions avoided from 1990 through 1992, because no data was reported for abandoned coal mine CH$_4$ recovery and use or destruction projects during that time.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted to estimate the uncertainty surrounding the estimates of CH_4 emissions from abandoned underground coal mines. The uncertainty analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the Inventory estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the parameters for which values must be estimated for each mine in order to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-36. Annual abandoned coal mine CH_4 emissions in 2019 were estimated to be between 4.6 and 7.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 19 percent above the 2019 emission estimate of 5.9 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed in 1972 and later years. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates exist.

Table 3-36: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	5.9	4.6	7.1	-22.4%	+19.2%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for abandoned coal mines, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from abandoned coal mines. Trends across the time series were analyzed to determine whether any corrective actions were needed.

3.6 Petroleum Systems (CRF Source Category 1B2a)

This IPCC category (1B2a) is for fugitive emissions, which per IPCC include emissions from leaks, venting, and flaring. Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil

production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as emissions from leaks, venting (including emissions from operational upsets), and flaring. Carbon dioxide emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. Note, CO_2 emissions in Petroleum Systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion chapter (see Section 3). Emissions of N_2O from petroleum systems are primarily associated with flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from petroleum systems in 2019 were 86.4 MMT CO_2 Eq., an increase of 47 percent from 1990, primarily due to increases in CO_2 emissions. Since 2009, total emissions increased by 64 percent and since 2018, total emissions increased by 16 percent. Total CO_2 emissions from petroleum systems in 2019 were 47.3 MMT CO_2 (47,269 kt CO_2), 3.9 times higher than in 1990. Total CO_2 emissions in 2019 were 2.5 times higher than in 2009 and 27 percent higher than in 2018. Total CH_4 emissions from petroleum systems in 2019 were 39.1 MMT CO_2 Eq. (1,563 kt CH_4), a decrease of 20 percent from 1990. Since 2009, total CH_4 emissions increased by less than 0.5 percent; and since 2018, CH_4 emissions increased by 5 percent. Total N_2O emissions from petroleum systems in 2019 were 0.05 MMT CO_2 Eq. (0.16 kt N_2O), 1.8 times higher than in 1990, 1.5 times higher than in 2009, and 13 percent higher than in 2018. Since 1990, U.S. oil production has increased by 67 percent. In 2019, production was 129 percent higher than in 2009 and 12 percent higher than in 2018.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate. Recalculations in petroleum systems in this year's Inventory include:

- Incorporation of an estimate for produced water
- Updates to well counts using the most recent data from Enverus
- Recalculations due to GHGRP submission revisions

The Recalculations Discussion section below provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounted for approximately 1 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2019. The predominant sources of CH_4 emissions from exploration are hydraulically fractured oil well completions. Other sources include well testing, well drilling, and well completions without hydraulic fracturing. Since 1990, exploration CH_4 emissions have decreased 91 percent, and while the number of hydraulically fractured wells completed increased by a factor of 2.9, there were decreases in the fraction of such completions without reduced emissions completions (RECs) or flaring (from 90 percent in 1990 to less than 1 percent in 2019). Emissions of CH_4 from exploration were highest in 2012, nearly 30 times higher than in 2019; and lowest in 2019. Emissions of CH_4 from exploration decreased 30 percent from 2018 to 2019, due to a decrease in hydraulically fractured oil well completions with flaring. Exploration accounts for 4 percent of total emissions (including leaks, vents, and flaring) from petroleum systems in 2019. Emissions of CO_2 from exploration in 2019 were 7 times higher than in 1990, and decreased by 28 percent from 2018, due to a decrease in hydraulically fractured oil well completions with flaring. Emissions of CO_2 from exploration were highest in 2014, around 33 percent higher than in 2019. Exploration accounts for nearly 2 percent of total N_2O emissions from petroleum systems in 2019. Emissions of N_2O from exploration in 2019 are 4.3 times higher than in 1990, and 37 percent lower than in 2018, due to the abovementioned changes in hydraulically fractured oil well completions with flaring.

Production. Production accounted for 96 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2019. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, gas engines, equipment leaks, produced water, and associated gas flaring. These six sources together accounted for 82 percent of the CH_4 emissions from production. Since 1990, CH_4 emissions from production have decreased by 16 percent due to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Overall, production segment CH_4 emissions increased by 5 percent from 2018 levels due primarily to increased associated gas venting and flaring emissions in the Gulf Coast and Williston basins. Production emissions account for 85 percent of the total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2019. The principal sources of CO_2 emissions are associated gas flaring, miscellaneous production flaring, and oil tanks with flares. These three sources together account for 98 percent of the CO_2

emissions from production. In 2019, CO_2 emissions from production were 3.9 times higher than in 1990, due to increases in flaring emissions from associated gas flaring, miscellaneous production flaring, and tanks. Overall, production segment CO_2 emissions increased by 32 percent from 2018 levels primarily due to an increase in associated gas flaring in the Williston Basin. Production emissions accounted for 67 percent of the total N_2O emissions from petroleum systems in 2019. The principal sources of N_2O emissions are associated gas flaring, oil tanks with flares, and miscellaneous production flaring. In 2019, N_2O emissions from production were 3.2 times higher than in 1990 and 2.5 times higher than in 2009, due primarily to increases in N_2O from associated gas flaring. In 2019, N_2O emissions from production increased by 6 percent from 2018 levels.

Crude Oil Transportation. Emissions from crude oil transportation account for a very small percentage of the total emissions (including leaks, vents, and flaring) from petroleum systems and have little impact on the overall emissions. Crude oil transportation activities account for less than 1 percent of total CH_4 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 76 percent of CH_4 emissions from crude oil transportation. Since 1990, CH_4 emissions from transportation have increased by 40 percent. In 2019, CH_4 emissions from transportation increased by 8 percent from 2018 levels. Crude oil transportation activities account for less than 0.01 percent of total CO_2 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 76 percent of CO_2 emissions from crude oil transportation.

Crude Oil Refining. Crude oil refining processes and systems account for 2 percent of total fugitive (including leaks, vents, and flaring) CH_4 emissions from petroleum systems. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is an insignificant amount of CH_4 in all refined products. Within refineries, flaring accounts for 47 percent of the CH_4 emissions, while uncontrolled blowdowns, delayed cokers, and process vents account for 15, 12, and 10 percent, respectively. Fugitive CH_4 emissions from refining of crude oil have increased by 32 percent since 1990, and increased 16 percent from 2018; however, like the transportation subcategory, this increase has had little effect on the overall emissions of CH_4 from petroleum systems. Crude oil refining processes and systems account for 11 percent of total fugitive (including leaks, vents, and flaring) CO_2 emissions from petroleum systems. Of the total fugitive CO_2 emissions from refining, almost all (about 99 percent) of it comes from flaring.[75] Since 1990, refinery fugitive CO_2 emissions increased by 53 percent and have increased by 34 percent from the 2018 levels, due to an increase in flaring. Flaring occurring at crude oil refining processes and systems accounts for 31 percent of total fugitive N_2O emissions from petroleum systems. Refinery fugitive N_2O emissions increased by 61 percent from 1990 to 2019 and increased by 40 percent from 2018 levels.

Table 3-37: Total Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Exploration	3.3		4.9		4.2	1.7	2.1	3.3	2.4
Production	51.2		42.0		64.6	54.4	57.5	66.4	77.9
Transportation	0.2		0.1		0.2	0.2	0.2	0.2	0.2
Crude Refining	4.0		4.5		4.9	4.8	4.6	4.5	5.9
Total	**58.6**		**51.5**		**73.9**	**61.1**	**64.4**	**74.5**	**86.4**

Note: Totals may not sum due to independent rounding.

Table 3-38: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Exploration	**3.0**		**4.5**		**2.1**	**0.5**	**0.4**	**0.4**	**0.3**

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[75] Petroleum Systems includes fugitive emissions (leaks, venting, and flaring). In many industries, including petroleum refineries, the largest source of onsite CO_2 emissions is often fossil fuel combustion, which is covered in section 3.1 of this chapter.

Production	**45.1**	**34.0**	**38.4**	**37.7**	**38.0**	**35.9**	**37.7**
Pneumatic Controllers	19.8	16.8	18.8	19.6	20.0	17.3	17.5
Offshore Production	9.3	6.5	5.5	5.1	5.1	5.0	5.0
Gas Engines	2.2	1.8	2.5	2.4	2.4	2.4	2.4
Equipment Leaks	2.0	2.0	2.5	2.4	2.4	2.4	2.3
Produced Water	2.3	1.6	2.1	1.9	2.0	2.1	2.1
Assoc Gas Flaring	0.5	0.4	1.2	0.7	1.0	1.7	2.0
Other Sources	8.9	4.9	5.8	5.5	5.2	5.1	6.2
Crude Oil Transportation	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**
Total	**48.9**	**39.5**	**41.5**	**39.2**	**39.3**	**37.3**	**39.1**

Note: Totals may not sum due to independent rounding.

Table 3-39: CH_4 Emissions from Petroleum Systems (kt CH_4)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	**119**	**182**	**83**	**19**	**14**	**15**	**11**
Production	**1,802**	**1,361**	**1,535**	**1,508**	**1,519**	**1,438**	**1,507**
Pneumatic Controllers	792	673	750	785	799	694	699
Offshore Production	374	261	221	206	205	199	201
Gas Engines	88	74	99	95	94	96	98
Equipment Leaks	82	81	101	97	96	95	94
Produced Water	91	62	82	77	79	83	85
Assoc Gas Flaring	20	15	49	29	38	68	82
Other Sources	355	196	233	219	207	203	249
Crude Oil Transportation	**7**	**5**	**8**	**8**	**8**	**8**	**9**
Refining	**27**	**31**	**33**	**33**	**33**	**31**	**36**
Total	**1,955**	**1,579**	**1,659**	**1,568**	**1,574**	**1,492**	**1,563**

Note: Totals may not sum due to independent rounding.

Table 3-40: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	0.3	0.3	2.2	1.2	1.7	2.9	2.1
Production	6.1	8.0	26.2	16.6	19.6	30.5	40.2
Transportation	+	+	+	+	+	+	+
Crude Refining	3.3	3.7	4.1	4.0	3.7	3.7	5.0
Total	**9.7**	**12.1**	**32.4**	**21.8**	**25.0**	**37.1**	**47.3**

Note: Totals may not sum due to independent rounding.

Table 3-41: CO_2 Emissions from Petroleum Systems (kt CO_2)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	313	340	2,182	1,212	1,700	2,906	2,081
Production	6,111	7,991	26,163	16,643	19,564	30,473	40,168
Transportation	0.9	0.7	1.2	1.1	1.1	1.2	1.3
Crude Refining	3,284	3,728	4,067	3,991	3,714	3,735	5,019
Total	**9,709**	**12,059**	**32,412**	**21,847**	**24,979**	**37,115**	**47,269**

Note: Totals may not sum due to independent rounding.

Table 3-42: N₂O Emissions from Petroleum Systems (Metric Tons CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	162	173	1,118	617	744	1,370	860
Production	7,502	8,050	20,300	15,087	15,812	29,636	31,269
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	9,138	10,372	11,656	11,575	10,796	10,557	14,749
Total	**16,802**	**18,596**	**33,074**	**27,279**	**27,352**	**41,562**	**46,878**

Note: Totals may not sum due to independent rounding.
NE (Not Estimated)

Table 3-43: N₂O Emissions from Petroleum Systems (Metric Tons N₂O)

Activity	1990	2005	2015	2016	2017	2018	2019
Exploration	0.5	0.6	3.8	2.1	2.5	4.6	2.9
Production	25.2	27.0	68.1	50.6	53.1	99.4	104.9
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	30.7	34.8	39.1	38.8	36.2	35.4	49.5
Total	**56.4**	**62.4**	**111.0**	**91.5**	**91.8**	**139.5**	**157.3**

Note: Totals may not sum due to independent rounding.
NE (Not Estimated)

Methodology

See Annex 3.5 for the full time series of emissions data, activity data, emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed with a Tier 3 approach (i.e., all refineries in the nation report emissions data for these sources to the GHGRP, and they are included in the estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

EPA received stakeholder feedback on updates in the Inventory through EPA's stakeholder process on oil and gas in the Inventory. Stakeholder feedback is noted below in Recalculations Discussion and Planned Improvements. More information on the stakeholder process can be found here: https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Emission Factors. Key references for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (GRI/EPA 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997)*, Global Emissions of Methane from Petroleum Sources* (API 1992), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports, *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017), and analysis of GHGRP data (EPA 2020).

Emission factors for hydraulically fractured (HF) oil well completions and workovers (in four control categories) were developed using EPA's GHGRP data; year-specific data were used to calculate emission factors from 2016-forward and the year 2016 emission factors were applied to all prior years in the time series. The emission factors for all years for pneumatic controllers and chemical injection pumps were developed using GHGRP data for reporting year 2014. The emission factors for tanks, well testing, and associated gas venting and flaring were developed using year-specific GHGRP data for years 2015 forward; earlier years in the time series use 2015

emission factors. For miscellaneous production flaring, year-specific emission factors were developed for years 2015 forward from GHGRP data, an emission factor of 0 (assumption of no flaring) was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. For more information, please see memoranda available online.[76] For offshore oil production, emission factors were calculated using BOEM data for offshore facilities in federal waters of the Gulf of Mexico (and these data were also applied to facilities located in state waters of the Gulf of Mexico) and GHGRP data for offshore facilities off the coasts of California and Alaska. For many other sources, emission factors were held constant for the period 1990 through 2019, and trends in emissions reflect changes in activity levels. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 forward contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko. For miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. For each source, data from all other basins were combined, and activity and emission factors were developed for the other basins as a single group.

For the exploration and production segments, in general, CO_2 emissions for each source were estimated with GHGRP data or by multiplying CO_2 content factors by the corresponding CH_4 data, as the CO_2 content of gas relates to its CH_4 content. Sources with CO_2 emission estimates calculated using GHGRP data include HF completions and workovers, associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, miscellaneous production flaring, and certain offshore production facilities (those located off the coasts of California and Alaska). For these sources, CO_2 was calculated using the same methods as used for CH_4. Carbon dioxide emission factors for offshore oil production in the Gulf of Mexico were derived using data from BOEM, following the same methods as used for CH_4 estimates. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For the exploration and production segments, N_2O emissions were estimated for flaring sources using GHGRP or BOEM OGOR-B data and the same method used for CO_2. Sources with N_2O emissions in the exploration segment include well testing and HF completions with flaring. Sources with N_2O emissions in the production segment include associated gas flaring, tank flaring, miscellaneous production flaring, HF workovers with flaring, and flaring from offshore production sources.

For crude oil transportation, emission factors for CH_4 were largely developed using data from EPA (1997), API (1992), and EPA (1999). Emission factors for CO_2 were estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in whole crude post-separator.

For petroleum refining activities, year-specific emissions from 2010 forward were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in 2010. The reported total CH_4, CO_2, and N_2O emissions for each activity was used for the emissions in each year from 2010 forward. To estimate emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed) and 2010 to 2017 data were used to derive N_2O emission factors; these emission factors were then applied to the annual refinery feed in years 1990 to 2009. GHGRP delayed coker CH_4 emissions for 2010 through 2017 were increased using the ratio of certain reported emissions for 2018 to 2017, to account for a more accurate GHGRP calculation methodology that was implemented starting in reporting year 2018.

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[76] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

Activity Data. References for activity data include Enverus data (Enverus 2021), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2020).

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI 1996 and/or GHGRP data. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI 1996. Lastly, in limited instances the previous year's data were used if current year data were not yet available.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5. The U.S. reports data to the UNFCCC using this Inventory report along with Common Reporting Format (CRF) tables. This note is provided for those reviewing the CRF tables: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRF table 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty and Time-Series Consistency

EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize uncertainty for petroleum systems. For more information on the approach, please see the memorandum Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates (2018 Uncertainty Memo).[77]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from petroleum systems for the current Inventory. Uncertainty estimates for N_2O were not developed given the minor contribution of N_2O to emission totals. For the CH_4 uncertainty analysis, EPA focused on the eight highest methane-emitting sources for the year 2019, which together emitted 76 percent of methane from petroleum systems in 2019, and extrapolated the estimated uncertainty for the remaining sources. Uncertainty was not previously estimated specifically for CO_2 emissions, instead the uncertainty bounds calculated for CH_4 were applied to CO_2 emissions estimates. As part of the stakeholder process for the current Inventory, EPA developed an update to the uncertainty analysis for CO_2. The update is documented in the memorandum, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates.*[78] EPA ultimately applied the same approach as was developed for CH_4. For the CO_2 uncertainty analysis, EPA focused on the 3 highest-emitting sources for the year 2018 (from the previous 1990-2018 Inventory), which together emitted 80 percent of CO_2 from petroleum systems in 2018, and extrapolated the estimated uncertainty for the remaining sources. The CO_2 uncertainty calculations were developed as part of the stakeholder process and were based on the previous 1990-2018 Inventory; as a result, the uncertainty results from last year's Inventory for year 2018 are applied for this year's uncertainty analysis. In future years, the CO_2 uncertainty bounds will be calculated using the most recent Inventory data. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties

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[77] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.
[78] Stakeholder materials, including draft and final memoranda for the current (i.e. 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2019, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-44. Petroleum systems CH_4 emissions in 2019 were estimated to be between 29.7 and 50.3 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 34.5 and 66.7 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, associated gas venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., reduced emissions completions were not used early in the time series).

Table 3-44: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	39.1	29.7	50.3	-24%	+29%
Petroleum Systems	CO_2	47.3	34.5	66.7	-27%	+41%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2019 CH_4 and year 2018 CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

EPA's GHGRP data, available starting in 2010 for refineries and in 2011 for other sources, have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2009 or 2014 by interpolating activity data or emission factors or both between 1992 (when GRI/EPA data are available) and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology Discussion above and Annex 3.5. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The petroleum systems emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC

analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[79]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder webinars on greenhouse gas data for oil and gas in September and November of 2020. EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Recalculations Discussion and Planned Improvements sections below.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed, and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates.

One comment on the public review draft suggested that the inventory estimates be compared with an observational analysis from a 2019 Lan et al. study.[80] Lan et al. estimated an average increasing trend of U.S. oil and gas methane emissions of 3.4 percent +/-1.4 percent per year between 2006 and 2015, based on three U.S. measurement sites that were "substantially influenced by O&NG activities." This study did not address the magnitude of emissions. Nationally, in the Inventory, methane emissions from oil and gas decreased by an average of 1 percent per year from 2006 to 2015, largely driven by the natural gas distribution and transmission and storage segments. A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the Inventory and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level Inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[81] The gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[82] An updated version of the gridded inventory is being developed and will improve efforts to compare results of the inventory with atmospheric studies.

As discussed above, refinery emissions are quantified by using the total emissions reported to GHGRP for the refinery emission categories included in Petroleum Systems. Subpart Y has provisions that refineries are not required to report under Subpart Y if their emissions fall below certain thresholds. Each year, a review is conducted to determine whether an adjustment is needed to the Inventory emissions to include emissions from refineries that stopped reporting to the GHGRP. The 2019 GHGRP data indicates that 3 refineries stopped reporting in 2019

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[79] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

[80] See <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018GL081731>.

[81] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>.

[82] See <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014>.

(i.e., 2018 is the last reported year). Two of the refineries ceased refinery operations permanently and the other was a refinery that discontinued reporting in 2019 without a valid reason. EPA did not adjust the 2019 refinery emissions in the Inventory but will further consider if adjustments are warranted in the future for the refinery that discontinued reporting without a valid reason.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. In September 2020, EPA released a draft memorandum that discussed changes under consideration to estimate emissions from produced water and requested stakeholder feedback on those changes. EPA then created an updated version of the memorandum to document the methodology implemented in the current Inventory.[83] The EPA memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Produced Water Emissions* (*Produced Water* memo) is cited below.

EPA thoroughly evaluated relevant information available and made an update to include an estimate for produced water emissions, discussed in detail below. In addition, certain sources did not undergo methodological updates, but CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2018 to the current (recalculated) estimate for 2018. For the sources without methodological updates, the emissions changes were mostly due to GHGRP data submission revisions and well count updates Enverus updates. These sources are also discussed below and include hydraulically fractured oil well completions, associated gas flaring, miscellaneous production flaring, production storage tanks, pneumatic controllers, chemical injection pumps, oil wellheads (leaks), and gas engines.

The combined impact of revisions to 2018 petroleum systems CH_4 emission estimates, compared to the previous Inventory, is an increase from 36.2 to 39.4 MMT CO_2 Eq. (3.2 MMT CO_2 Eq., or 9 percent). The recalculations resulted in an average increase in CH_4 emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 1.1 MMT CO_2 Eq., or 3 percent, with the largest increase being in the estimate for 1990 (2.8 MMT CO_2 Eq. or 6 percent) primarily due to inclusion of produced water estimates.

The combined impact of revisions to 2018 petroleum systems CO_2 emission estimates, compared to the previous Inventory, is an increase from 36.8 to 37.1 MMT CO_2 (0.3 MMT CO_2, or less than 1 percent). The recalculations resulted in an average decrease in emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 0.1 MMT CO_2 Eq., or 0.4 percent with the largest changes being for 2016 (1.1 MMT CO_2 or 5 percent) primarily due to the recalculations for flaring from tanks.

The combined impact of revisions to 2018 petroleum systems N_2O emission estimates, compared to the previous Inventory, is a decrease of 0.03 MMT CO_2, Eq. or 41 percent. The emission changes were primarily driven by reduction in flaring emissions from storage tanks and miscellaneous production flaring due to GHGRP data submission revisions. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 0.001 MMT CO_2 Eq., or 2 percent.

In Table 3-45 and Table 3-46 below are categories in Petroleum Systems with updated methodologies or with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2018 to the current (recalculated) estimate for 2018. For more information, please see the discussion below.

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[83] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

Table 3-45: Recalculations of CO₂ in Petroleum Systems (MMT CO₂)

Segment/Source	*Previous Estimate Year 2018, 2020 Inventory*	Current Estimate Year 2018, 2021 Inventory	Current Estimate Year 2019, 2021 Inventory
Exploration	*2.8*	**2.9**	**2.1**
HF Oil Well Completions	*2.7*	2.9	2.1
Production	*30.3*	**30.5**	**40.2**
Produced Water	*NE*	0.0	0.0
Tanks	*6.4*	6.3	6.1
Associated Gas Flaring	*19.0*	19.3	25.4
Miscellaneous Flaring	*4.2*	4.2	7.9
Transportation	*+*	**+**	**+**
Refining	*3.7*	**3.7**	**5.0**
Petroleum Systems Total	*36.8*	**37.1**	**47.3**

+ Does not exceed 0.05 MMT CO₂.
NE (Not Estimated)

Table 3-46: Recalculations of CH₄ in Petroleum Systems (MMT CO₂ Eq.)

Segment/Source	*Previous Estimate Year 2018, 2020 Inventory*	Current Estimate Year 2018, 2021 Inventory	Current Estimate Year 2019, 2021 Inventory
Exploration	*0.4*	**0.4**	**0.3**
HF Oil Well Completions	*0.3*	0.4	0.2
Production	*34.9*	**35.9**	**37.7**
Produced Water	*NE*	2.1	2.1
Pneumatic Controllers	*18.4*	17.3	17.5
Associated Gas Flaring	*1.3*	1.7	2.0
Miscellaneous Flaring	*0.4*	0.3	0.6
Chemical InjectionPumps	*2.0*	1.9	1.9
Oil Wellheads (Leaks)	*1.5*	1.4	1.4
Gas Engines	*2.3*	2.4	2.4
Transportation	*0.2*	**0.2**	**0.2**
Refining	*0.8*	**0.8**	**0.9**
Petroleum Systems Total	*36.2*	**39.4**	**41.2**

NE (Not Estimated)

Exploration

HF Oil Well Completions (Recalculation with Updated Data)

HF oil well completion CO₂ emissions decreased by an average of 1 percent across the time series and increased by 5 percent in 2018, compared the to the previous Inventory. The emissions changes were due to GHGRP data submission revisions.

Table 3-47: HF Oil Well Completions National CO₂ Emissions (kt CO₂)

Source	1990		2005		2015	2016	2017	2018	2019
HF Completions: Non-REC with Venting	2.5		4.0		1.4	0.2	0.2	+	+
HF Completions: Non-REC with Flaring	88		140		439	248	394	574	795
HF Completions: REC with Venting	0.0		0.0		0.2	0.1	0.1	0.1	0.1
HF Completions: REC with Flaring	0.0		0.0		1,494	926	1,270	2,300	1,283
Total Emissions	**91**		**144**		**1,935**	**1,174**	**1,664**	**2,874**	**2,078**

Previous Estimate		92	143	1,966	1,192	1,529	2,730	NA

+ Does not exceed 0.05 kt CO_2.
NA (Not Applicable)

Production

Produced Water (Methodological Update)

EPA developed a new calculation methodology to estimate produced water emissions from oil wells. Previous Inventories did not include emissions from produced water from oil wells. EPA's considerations for this source are documented in the *Produced Water* Memo.[84] Produced water quantities (i.e., bbl) were obtained for 36 oil-producing states as described below:

- Produced water quantities for 1990-2019 were obtained using DrillingInfo and Prism datasets from Enverus for 29 states (i.e., AK, AL, AR, AZ, CA, CO, FL, ID, KY, LA, MD, MI, MN, MO, MS, MT, NC, ND, NE, NM, NV, NY, OR, SD, TN, TX, UT, VA, and WY) (Enverus 2021). Linear interpolation was used to correct an obviously inaccurate near-zero produced water quantity value in Colorado for 1998.
- For four additional states, produced water quantities for 1990-2018 were obtained from state agency websites – KS (Kansas Department of Health and Environment 2020), OH (Ohio Environmental Protection Agency 2020), OK (Oklahoma Department of Environmental Quality 2020), and PA (Pennsylvania Department of Environmental Protection 2020). Produced water quantities for 2018 were used as proxy data for 2019 for these four states.
- Produced water quantities for 1990-2018 were estimated for three states (IL, IN, and WV) using state-level produced water production ratios for oil wells. Well-level produced water data for oil wells for 2011 were obtained from the DrillingInfo dataset (Enverus 2021) and oil production data were obtained from state agency websites – IL (Illinois Office of Oil and Gas Resource Management 2020), IN (Indiana Division of Oil & Gas 2020), and WV (West Virginia Department of Environmental Protection 2020). Using these well-level produced water data and the oil production data, production ratios were developed for oil wells in each state. These production ratios were then applied to annual state-level oil production data (2000-2018) from EIA (EIA 2020). Produced water quantities for 2018 were used as proxy data for 2019 for these three states.

Based upon findings of the CenSARA emissions inventory (CenSARA 2012), EPA assumed that 73 percent of the produced water was from low pressure oil wells (i.e., wells requiring artificial lifts) and that 27 percent of the produced water was from regular pressure oil wells (i.e., wells not requiring artificial lifts).. EPA applied emission factors unique to low pressure and regular pressure oil wells, obtained from the Production Module of the 2017 Oil and Gas Tool. Produced water CH_4 emissions average 73,000 mt CH_4, over the 1990 to 2019 time series.

EPA received feedback on this update through its September 2020 memo and through the public review draft of the inventory.

A stakeholder indicated that the typical practice is to route produced water to a tank battery, once it reaches the surface and has been separated from the oil and gas. A stakeholder requested that data from the latest 2017 Ground Water Protection Council produced water management practices survey be used to determine the percent of produced water that is stored in tanks. The stakeholder indicated that approximately 16 percent of produced water has the potential of being stored in a tank battery that could potentially flash (based on the 2012 Ground Water Protection Council produced water management practices survey). After further assessment of the 2012 and 2017 water management practice surveys, EPA has maintained the assumption that all produced water goes through tanks and emissions are flashed, consistent with the approach used for the public review draft of the Inventory.

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[84] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

A stakeholder commented that current regulations under 40 CFR 60 subpart OOOOa require that certain storage vessels route emission vapors to a recovery device, flare, or other control device. EPA currently does not have specific data to address the use of controls on produced water tanks but will continue to assess this issue in future inventories should additional data become available.

Table 3-48: Produced Water National CH$_4$ Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Low Pressure Oil Wells	20,292		13,794		18,276	17,142	17,446	18,368	18,794
Regular Pressure Oil Wells	71,186		48,390		64,115	60,136	61,273	64,438	65,931
Total	**91,478**		**62,184**		**82,392**	**77,278**	**78,739**	**82,806**	**84,726**
Previous Estimate	*NA*		*NA*		*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

Tanks (Recalculation with Updated Data)

Tank CO$_2$ emissions estimates increased by an average of 2 percent across the 1990 to 2018 time series and decreased by 1 percent in 2018, compared to the previous inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-49: Tanks National CO$_2$ Emissions (kt CO$_2$)

Source	1990		2005		2015	2016	2017	2018	2019
Large Tanks w/Flares	0		2,451		7,074	4,489	4,298	6,219	6,037
Large Tanks w/VRU	0		5		14	3	4	4	7
Large Tanks w/o Control	24		6		6	5	5	4	5
Small Tanks w/Flares	0		2		7	13	11	8	10
Small Tanks w/o Flares	6		3		5	4	4	4	4
Malfunctioning Separator Dump Valves	86		*50*		104	32	43	39	34
Total Emissions	**116**		***2,517***		**7,209**	**4,546**	**4,364**	**6,278**	**6,098**
Previous Estimate	*46*		*2,641*		*7,584*	*5,913*	*4,413*	*6,369*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Recalculation with Updated Data)

Pneumatic controller CH$_4$ emission estimates decreased by an average of 3 percent across the 1990 to 2018 time series and decreased by 6 percent in 2018, compared to the previous Inventory. The emission changes were due to GHGRP data submission revisions and updated Enverus well counts.

Table 3-50: Pneumatic Controller National CH$_4$ Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
High Bleed	741,469		401,564		73,505	77,866	57,020	45,304	49,775
Low Bleed	50,606		42,080		23,868	16,358	18,283	28,496	34,092
Intermittent Bleed	0		229,126		652,946	690,799	724,193	620,175	615,621
Total Emissions	**792,075**		**672,769**		**750,320**	**785,023**	**799,496**	**693,976**	**699,488**
Previous Estimate	*772,311*		*704,401*		*789,484*	*822,989*	*850,624*	*734,824*	*NA*

NA (Not Applicable)

Associated Gas Flaring (Recalculation with Updated Data)

Associated gas flaring CO_2 emission estimates increased by an average of 1 percent across the time series and increased by 2 percent in 2018 in the current Inventory, compared to the previous Inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-51: Associated Gas Flaring National CO_2 Emissions (kt CO_2)

Source	1990		2005		2015	2016	2017	2018	2019
220 - Gulf Coast Basin (LA, TX)	227		121		672	404	744	643	584
360 - Anadarko Basin	108		66		242	1	64	82	18
395 - Williston Basin	987		1,263		8,567	6,091	6,908	11,140	16,572
430 - Permian Basin	2,983		2,056		4,468	2,261	3,209	6,782	7,161
"Other" Basins	935		505		548	324	387	641	1,021
Total Emissions	**5,241**		**4,011**		**14,498**	**9,081**	**11,313**	**19,287**	**25,356**
220 - Gulf Coast Basin (LA, TX)	*234*		*127*		*673*	*404*	*740*	*686*	*NA*
360 - Anadarko Basin	*108*		*65*		*238*	*2*	*57*	*37*	*NA*
395 - Williston Basin	*966*		*1,239*		*8,412*	*5,838*	*6,530*	*10,132*	*NA*
430 - Permian Basin	*2,983*		*2,046*		*4,443*	*2,246*	*3,148*	*7,249*	*NA*
"Other" Basins	*925*		*499*		*544*	*326*	*414*	*876*	*NA*
Previous Estimate	*5,217*		*3,977*		*14,311*	*8,815*	*10,889*	*18,980*	*NA*

NA (Not Applicable)

Associated gas flaring CH_4 emission estimates increased by an average of 2 percent across the time series in the current Inventory, compared to the previous inventory. The CH_4 estimates increased by 27 percent in 2018, primarily due to Williston Basin data. The emission changes were due to GHGRP data submission revisions.

Table 3-52 Associated Gas Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990		2005		2015	2016	2017	2018	2019
220 - Gulf Coast Basin (LA, TX)	896		479		2,654	1,572	2,936	2,448	2,626
360 - Anadarko Basin	472		288		1,056	4	277	358	87
395 - Williston Basin	2,931		3,750		25,437	16,948	20,707	37,754	48,453
430 - Permian Basin	11,815		8,143		17,696	8,972	13,189	25,511	27,016
"Other" Basins	4,328		2,335		2,538	1,193	1,290	1,932	3,614
Total Emissions	**20,441**		**14,995**		**49,380**	**28,689**	**38,399**	**68,004**	**81,797**
220 - Gulf Coast Basin (LA, TX)	*922*		*500*		*2,659*	*1,572*	*2,918*	*2,779*	*NA*
360 - Anadarko Basin	*471*		*285*		*1,038*	*7*	*252*	*190*	*NA*
395 - Williston Basin	*2,874*		*3,686*		*25,020*	*16,151*	*20,130*	*26,011*	*NA*
430 - Permian Basin	*11,816*		*8,104*		*17,596*	*8,913*	*12,974*	*22,597*	*NA*
"Other" Basins	*4,274*		*2,306*		*2,514*	*1,196*	*1,388*	*1,862*	*NA*
Previous Estimate	*20,357*		*14,881*		*48,826*	*27,839*	*37,662*	*53,438*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CH_4 emission estimates decreased by 27 percent in 2018 and decreased by an average of 4 percent for other years of the time series, compared to the previous Inventory. The 2018 decrease was primarily due to recalculations in the Permian and Gulf Coast basins, where GHGRP data showed lower CH_4 flaring emissions, by 47 and 18 percent, respectively. The emission changes were due to GHGRP data submission revisions.

Table 3-53: Miscellaneous Production Flaring National CH₄ Emissions (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
220 - Gulf Coast Basin (LA, TX)	0		410		4,021	1,979	2,179	1,951	2,554
395 - Williston Basin	0		182		2,184	854	1,618	3,045	3,904
430 - Permian Basin	0		807		3,103	2,812	5,055	4,449	14,151
Other Basins	0		1,316		2,806	1,455	1,960	1,891	1,847
Total Emissions	**0**		**2,715**		**12,114**	**7,101**	**10,812**	**11,336**	**22,457**
220 - Gulf Coast Basin (LA, TX)	*0*		*424*		*3,985*	*1,979*	*2,164*	*2,370*	*NA*
395 - Williston Basin	*0*		*191*		*2,293*	*888*	*1,603*	*2,947*	*NA*
430 - Permian Basin	*0*		*805*		*3,091*	*2,794*	*5,024*	*8,406*	*NA*
Other Basins	*0*		*1,440*		*3,074*	*1,452*	*2,018*	*1,812*	*NA*
Previous Total Estimate	*0*		*2,859*		*12,443*	*7,113*	*10,810*	*15,536*	*NA*

NA (Not Applicable)

Miscellaneous production flaring CO_2 emission estimates decreased by 1 percent in 2018 and decreased by less than 0.5 percent for other years of the time series, compared to the previous Inventory. The 2018 decrease was primarily due to recalculations of CO_2 from flaring in the Gulf Coast Basin, where GHGRP data showed lower CO_2 emissions from flaring, by 16 percent. The emission changes were due to GHGRP data submission revisions.

Table 3-54: Miscellaneous Production Flaring National CO₂ Emissions (kt CO₂)

Source	1990		2005		2015	2016	2017	2018	2019
220 - Gulf Coast Basin (LA, TX)	0		102		1,004	497	526	577	625
395 - Williston Basin	0		73		873	304	537	1,706	2,934
430 - Permian Basin	0		215		828	799	1,433	1,244	3,701
Other Basins	0		408		870	593	568	640	689
Total Emissions	**0**		**799**		**3,575**	**2,192**	**3,063**	**4,167**	**7,949**
220 - Gulf Coast Basin (LA, TX)	*0*		*106*		*997*	*497*	*526*	*687*	*NA*
395 - Williston Basin	*0*		*73*		*882*	*315*	*531*	*1,653*	*NA*
430 - Permian Basin	*0*		*215*		*825*	*794*	*1,424*	*1,183*	*NA*
Other Basins	*0*		*407*		*870*	*592*	*585*	*703*	*NA*
Previous Total Estimate	*0*		*801*		*3,573*	*2,198*	*3,066*	*4,226*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH_4 emission estimates decreased by an average of 4 percent across the time series and decreased by 6 percent in 2018, compared to the previous Inventory. The emission changes were due to updated Enverus well counts.

Table 3-55: Chemical Injection Pump National CH₄ Emissions (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
Chemical Injection Pump	50,806		64,259		81,103	78,351	77,061	76,014	75,182
Previous Estimate	*49,368*		*68,097*		*86,529*	*83,705*	*82,180*	*81,294*	*NA*

NA (Not Applicable)

Oil Wellheads (Recalculation with Updated Data)

Oil wellhead CH_4 emission estimates decreased by an average of 8 percent across the time series and decreased by 6 percent in 2018, compared to the previous Inventory. The emission changes were due to updated Enverus well counts.

Table 3-56: Oil Wellhead National CH_4 Emissions (Metric Tons CH_4)

Source	1990		2005		2015	2016	2017	2018	2019
Oil Wellheads (heavy crude)	32		28		35	34	34	33	33
Oil Wellheads (light crude)	55,064		48,648		61,163	59,088	58,115	57,326	56,699
Total Emissions	**55,096**		**48,676**		**61,199**	**59,122**	**58,149**	**57,359**	**56,732**
Previous Estimate	*61,144*		*52,504*		*65,294*	*63,162*	*62,011*	*61,343*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engine (combustion slip) CH_4 emission estimates increased by an average of 4 percent across the time series and increased by 5 percent in 2018, compared to the previous Inventory. The emission changes were due to updated Enverus well counts. Even though the well counts have decreased across the time-series, the 2018 gas engine estimates are calculated using the ratio of 2018 to 1993 well counts. Since the 1993 well counts show a larger decrease (-12%) compared to the 2018 well counts (-6%), the gas engine estimates increased.

Table 3-57: Gas Engine National CH_4 Emissions (Metric Tons CH_4)

Source	1990		2005		2015	2016	2017	2018	2019
Total Gas Engine Emissions	87,854		73,659		98,896	94,771	94,311	96,338	97,828
Previous Estimate	*85,744*		*69,999*		*93,414*	*89,565*	*89,063*	*91,459*	*NA*

NA (Not Applicable)

Well Counts (Recalculation with Updated Data)

EPA uses annual producing oil well counts as an input for estimates of emissions from multiple sources in the Inventory, including exploration well testing, pneumatic controllers, chemical injection pumps, well workovers, and equipment leaks. Annual well count data are obtained from Enverus for the entire time series during each Inventory cycle, and a new data processing methodology was implemented this year due to a restructuring of the Enverus well count data (Enverus 2021). Due to of the data restructuring and the new processing methodology, annual well counts decreased by an average of 8 percent across the 1990-2018 time series and decreased by 6 percent in 2018, compared to the previous Inventory.

Table 3-58: National Oil Well Counts

Source	1990		2005		2015	2016	2017	2018	2019
Oil Wells	506,730		447,683		562,857	543,759	534,806	527,544	521,771
Previous Estimate	*562,356*		*482,887*		*600,519*	*580,917*	*570,331*	*564,186*	*NA*

NA (Not Applicable)

In December 2020, EIA released an updated time series of national oil and gas well counts (covering 2000 through 2018). EIA estimates 969,136 total producing wells for year 2019. EPA's total well count for this year is 939,637. EPA's well counts are generally lower than EIA's (e.g., around 3 percent lower in 2019). EIA's well counts include side tracks (i.e., secondary wellbore away from original wellbore in order to bypass unusable formation, explore nearby formations, or other reasons), completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. EPA and EIA use a different threshold for distinguishing between oil versus gas (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells

(e.g., 44 percent versus EPA's 56 percent in 2019) and a higher fraction of gas wells (e.g., 56 percent versus EPA's 44 percent in 2019) than EPA.

Transportation

Recalculations for the transportation segment have resulted in an average increase in calculated CH_4 and CO_2 emissions over the time series from this segment of less than 0.02 percent, compared to the previous Inventory.

Refining

Recalculations due to resubmitted GHGRP data in the refining segment have resulted in an average increase in calculated CH_4 emissions over the time series from this segment of 0.1 percent and an average increase in calculated CO_2 emissions over the time series of less than 0.01 percent, compared to the previous Inventory.

Planned Improvements

Mud Degassing

As part of the stakeholder process for the current (1990 to 2019) Inventory, EPA developed draft CH_4 emission estimates for mud degassing in the onshore exploration segment. To date, the Inventory has not included emissions from onshore exploration mud degassing. EPA's considerations for this source are documented in the EPA memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update Under Consideration for Mud Degassing Emissions* (*Mud Degassing* Memo).[85] EPA estimated emissions using CH_4 emission factors from EPA (EPA 1977) and the count of wells drilled from Enverus DrillingInfo data (Enverus DrillingInfo 2019). To calculate emissions per well drilled, EPA incorporated an estimate of 26 days as an average drilling duration and 61.2 percent (by weight) as the default CH_4 content of associated gas. EPA developed national estimates for two different scenarios: 1) EPA assumed 80 percent of drilling operations were performed using water-based muds and the remaining 20 percent used oil-based muds; and 2) EPA assumed 100 percent of drilling operations were performed using water-based muds. Mud degassing CH_4 emissions averaged 107 kt over the time series for scenario 1 and 126 kt for scenario 2, or around 3 MMT CO_2 Eq. This update would increase emissions from the exploration segment but would have a small impact on overall CH_4 emissions from petroleum systems.

EPA notes that estimates for mud degassing using similar assumptions are included in several other bottom-up inventories for greenhouse gases and other gases, including New York state and the NEI.

EPA received feedback on this update through its September 2020 memo and through the public review draft of the Inventory. A stakeholder indicated the 12 inch diameter borehole and 25 percent formation porosity assumptions used in developing the CH_4 emission factor for water-based muds are outdated and recommended that an 8 inch borehole diameter and 10 percent porosity should be considered in developing the CH_4 EF. A stakeholder commented that current onshore practices are to drill with balanced or slightly over-balanced mud systems that keep gas from being entrained in the drilling mud and that mud degassing systems are rarely needed or used. A stakeholder also indicated that mainly oil-based muds are used for horizontal/lateral drilling and water-based muds are more frequently used for vertical drilling.

Additionally, EPA also received comments on the average drilling duration used in developing the draft estimates for onshore mud degassing. A stakeholder commentstated that EPA should only consider the duration the drill spends in the producing formation. Another comment indicated that EPA's average drilling duration assumption of 26 days per well is high and presented 2 examples – a Marcellus well takes 10 days to drill with 2-3 days in the producing formation; and the drilling duration in the Fayetteville shale dropped from 20 days in 2007 to 11 days in 2009. EPA's average drilling duration assumption of 26 days per well is comparable to average drilling duration

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[85] Stakeholder materials including draft memoranda for the current (i.e., 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

developed from other inventories (New York – 24 days/well and CenSARA – 22 days/well). Refer to the *Mud Degassing* memo for further details.

EPA continues to seek feedback on average total drilling days and drilling days in the producing formation, CH_4 content of the gas, and the effect of balanced and over-balanced mud degassing systems. EPA will further assess the average drilling duration using updated Enverus data. Additionally, EPA is considering developing CO_2 estimates for onshore production mud degassing using the CH_4 estimates and a ratio of CO_2-to-CH_4.

Table 3-59: Draft Mud Degassing National CH₄ Emissions—Not Included in Totals (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
Scenario 1 (80/20)	105,862		98,024		93,555	56,256	101,179	101,179	101,179
Scenario 2 (100)	124,543		115,322		110,065	66,183	119,035	119,035	119,035
Previous Estimate	*NA*		*NA*		*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

Scenario 1 (80/20) = 80% water-based mud usage and 20% oil-based mud usage

Scenario 2 (100) = 100% water-based mud usage

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the Methane Challenge Program on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, in recent years, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank and flaring malfunction and control efficiency data.
- Improved equipment leak data
- Activity data and emissions data for production facilities that do not report to GHGRP.
- Associated gas venting and flaring data on practices from 1990 through 2010.
- Refineries emissions data.
- Anomalous leak events.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

Box 3-6: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications, or is stored geologically. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the Inventory, emissions of CO_2 from naturally-occuring CO_2 reservoirs are estimated based on the specific application.

In the Inventory, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section, 4.15.

For EOR CO_2, as noted in the *2006 IPCC Guidelines*, "At the Tier 1 or 2 methodology levels [EOR CO_2 is] indistinguishable from fugitive greenhouse gas emissions by the associated oil and gas activities." In the U.S. estimates for oil and gas fugitive emissions, the Tier 2 emission factors for CO_2 include CO_2 that was originally

injected and is emitted along with other gas from leak, venting, and flaring pathways, as measurement data used to develop those factors would not be able to distinguish between CO_2 from EOR and CO_2 occurring in the produced natural gas. Therefore, EOR CO_2 emitted through those pathways is included in CO_2 estimates in 1B2.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities reporting geologic sequestration of CO_2 to the GHGRP develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this inventory estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2019 and data reported for geologic sequestration from 2016 to 2019.

The amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2019 is 52,100 kt (52.1 MMT CO_2 Eq.) (see 6). The quantity of CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is generally assumed to be emitted and included in emissions totals from those processes.

Table 3-60: Quantity of CO₂ Captured and Extracted for EOR Operations (kt CO₂)

Stage	2015	2016	2017	2018	2019
Total CO_2 Captured and Extracted Stage	54,000	46,700	49,600	48,400	52,100

Several facilities are reporting under GHGRP subpart RR (Geologic Sequestration of Carbon Dioxide). See Table 3-61 for the number of facilities reporting under subpart RR, the reported CO_2 sequestered in subsurface geologic formations in each year, and of the quantity of CO_2 emitted from equipment leaks in each year. The quantity of CO_2 sequestered and emitted is noted here for information purposes only; EPA is considering updates to its approach in the Inventory for this source for future Inventories.

Table 3-61: Geologic Sequestration Information Reported Under GHGRP Subpart RR

Stage	2015	2016	2017	2018	2019
Number of Reporting Facilities	NA	1	3	5	5
Reported Annual CO_2 Sequestered (kt)	NA	3,091	5,958	7,662	8,332
Reported Annual CO_2 Emissions from Equipment Leaks (kt)	NA	10	10	11	16

3.7 Natural Gas Systems (CRF Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. This IPCC category (1B2b) is for fugitive emissions, which per IPCC include emissions from leaks, venting, and flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in 2019 were 194.9 MMT CO_2 Eq., a decrease of 11 percent from 1990, primarily due to decreases in CH_4 emissions, and an increase of 5 percent from 2018, primarily due to increases in CH_4 emissions. From 2009, emissions increased by 6 percent, primarily due to increases in CO_2 emissions. National total dry gas production in the United States increased by 91 percent from 1990 to 2019, by 10 percent from 2018 to 2019, and by 65 percent from 2009 to 2019. Of the overall greenhouse gas emissions (194.9 MMT CO_2 Eq.), 81 percent are CH_4 emissions (157.6 MMT CO_2 Eq.), 19 percent are CO_2 emissions (37.2 MMT), and less than 0.01 percent are N_2O emissions (0.01 MMT CO_2 Eq.).

Overall, natural gas systems emitted 157.6 MMT CO_2 Eq. (6,305 kt CH_4) of CH_4 in 2019, a 16 percent decrease compared to 1990 emissions, and 3 percent increase compared to 2018 emissions (see Table 3-63 and Table 3-64). For non-combustion CO_2, a total of 37.2 MMT CO_2 Eq. (37,234 kt) was emitted in 2019, a 16 percent increase compared to 1990 emissions, and a 10 percent increase compared to 2018 levels. The 2019 N_2O emissions were estimated to be 0.01 MMT CO_2 Eq. (0.04 kt N_2O), a 123 percent increase compared to 1990 emissions, and a 1 percent increase compared to 2018 levels.

The 1990 to 2019 trend is not consistent across segments or gases. Overall, the 1990 to 2019 decrease in CH_4 emissions is due primarily to the decrease in emissions from the following segments: distribution (69 percent decrease), transmission and storage (35 percent decrease), processing (42 percent decrease), and exploration (87 percent decrease). Over the same time period, the production segment saw increased CH_4 emissions of 59 percent (with onshore production emissions increasing 44 percent, offshore production emissions decreasing 82 percent, and gathering and boosting [G&B] emissions increasing 121 percent). The 1990 to 2019 increase in CO_2 emissions is primarily due to an increase in CO_2 emissions in the production segment, where emissions from flaring have increased over time.

Methane and CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include natural gas engine and turbine uncombusted exhaust, flaring, and leak emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Emissions of N_2O from flaring activities are included in the Inventory, with most of the emissions occurring in the processing and production segments. Note, CO_2 emissions exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in Section 3.1 – CO_2 from Fossil Fuel Combustion.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate. Recalculations in natural gas systems in this year's Inventory include:

- Updated methodology for produced water (to expand included basins)
- Updated methodology for customer meters to use data from GTI 2009 and GTI 2019
- Updates to well counts using the most recent data from Enverus
- Recalculations due to GHGRP submission revisions

The Recalculations Discussion section below provides more details on the updated methods.

Below is a characterization of the five major segments of the natural gas system: exploration, production (including gathering and boosting), processing, transmission and storage, and distribution. Each of the segments is described and the different factors affecting CH_4, CO_2, and N_2O emissions are discussed.

Exploration. Exploration includes well drilling, testing, and completions. Emissions from exploration accounted for less than 1 percent of CH_4 emissions and of CO_2 emissions from natural gas systems in 2019. Well completions accounted for approximately 95 percent of CH_4 emissions from the exploration segment in 2019, with the rest resulting from well testing and drilling. Flaring emissions account for most of the CO_2 emissions. Methane emissions from exploration decreased by 87 percent from 1990 to 2019, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs). Methane emissions decreased 36 percent from 2018 to 2019 due to decreases in emissions from hydraulically fractured well completions with RECs and venting. Methane emissions were highest from 2005 to 2008. Carbon dioxide emissions from exploration decreased by 44 percent from 1990 to 2019 and decreased 34 percent from 2018 to 2019 due to decreases in flaring. Carbon dioxide emissions were highest from 2006 to 2008. Nitrous oxide emissions decreased 73 percent from 1990 to 2019 and decreased 95 percent from 2018 to 2019.

Production (including gathering and boosting). In the production segment, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and from well-site equipment and activities such as pneumatic controllers, tanks and separators, and liquids unloading. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Boosting processes include compression, dehydration, and transport of gas to a processing facility or pipeline. Emissions from production (including gathering and boosting) accounted for 59 percent of CH_4 emissions and 29 percent of CO_2 emissions from natural gas systems in 2019. Emissions from gathering and boosting and pneumatic controllers in onshore production accounted for most of the production segment CH_4 emissions in 2019. Within gathering and boosting, the largest sources of CH_4 are compressor exhaust slip, compressor venting and leaks, and tanks. Flaring emissions account for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring. Methane emissions from production increased by 59 percent from 1990 to 2019, due primarily to increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers) and increases in emissions from compressor exhaust slip in gathering and boosting. Methane emissions increased 3 percent from 2018 to 2019 due to increases in the number of intermittent bleed controllers and increases in emissions from tanks in gathering and boosting. Carbon dioxide emissions from production increased by approximately a factor of 3.6 from 1990 to 2019 due to increases in emissions at flare stacks in gathering and boosting and miscellaneous onshore production flaring, and increased 11 percent from 2018 to 2019 due primarily to increases in emissions from flare stacks and acid gas removal in gathering and boosting. Nitrous oxide emissions increased 28 percent from 1990 to 2019 and increased 10 percent from 2018 to 2019. The increase in N_2O emissions from 1990 to 2019 and from 2018 to 2019 is primarily due to increase in emissions from flare stacks at gathering and boosting stations.

Processing. In the processing segment, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Methane emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants accounted for 8 percent of CH_4 emissions and 67 percent of CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 42 percent from 1990 to 2019 as emissions from compressors (leaks and venting) and equipment leaks decreased; and increased 3 percent from 2018 to 2019 due to increased emissions from gas engines. Carbon dioxide emissions from processing decreased by 13 percent from 1990 to 2019, due to a decrease in AGR emissions, and increased 7 percent from 2018 to 2019 due to increased emissions from flaring. Nitrous oxide emissions increased 39 percent from 2018 to 2019.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted compressor engine exhaust and

pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Leak and venting emissions from compressors are the primary contributors to CH_4 emissions from storage. Emissions from liquefied natural gas (LNG) stations and terminals are also calculated under the transmission and storage segment. Methane emissions from the transmission and storage segment accounted for approximately 23 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage accounted for 3 percent of the CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 35 percent from 1990 to 2019 due to reduced compressor station emissions (including emissions from compressors and leaks) and increased 6 percent from 2018 to 2019 due to increased emissions from transmission compressors. CO_2 emissions from transmission and storage were 6.9 times higher in 2019 than in 1990, due to increased emissions from LNG export terminals, and increased by 128 percent from 2018 to 2019, also due to LNG export terminals. The quantity of LNG exported from the U.S. increased by a factor of 35 from 1990 to 2019, and by 68 percent from 2018 to 2019. LNG emissions are about 1 percent of CH_4 and 80 percent of CO_2 emissions from transmission and storage in year 2019. Nitrous oxide emissions from transmission and storage increased by 145 percent from 1990 to 2019 and increased 169 percent from 2018 to 2019.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,316,689 miles of distribution mains in 2019, an increase of 372,532 miles since 1990 (PHMSA 2020). Distribution system emissions, which accounted for 9 percent of CH_4 emissions from natural gas systems and less than 1 percent of CO_2 emissions, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2019 were 69 percent lower than 1990 levels and 1 percent lower than 2018 emissions. Distribution system CO_2 emissions in 2019 were 69 percent lower than 1990 levels and 1 percent lower than 2018 emissions. Annual CO_2 emissions from this segment are less than 0.1 MMT CO_2 Eq. across the time series.

Total greenhouse gas emissions from the five major segments of natural gas systems are shown in MMT CO_2 Eq. in Table 3-62. Total CH_4 emissions for these same segments of natural gas systems are shown in MMT CO_2 Eq. (Table 3-63) and kt (Table 3-64). Most emission estimates are calculated using a net emission approach. However, a few sources are still calculated with a potential emission approach. Reductions data are applied to those sources that use a potential emissions approach. In recent years 6.3 MMT CO_2 Eq. CH_4 are subtracted from production segment emissions and 6.7 MMT CO_2 Eq. CH_4 are subtracted from the transmission and storage segment to calculate net emissions. More disaggregated information on potential emissions, net emissions, and reductions data is available in Annex 3.6, Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-62: Total Greenhouse Gas Emissions (CH₄, CO₂, and N₂O) from Natural Gas Systems (MMT CO₂ Eq.)

Stage	1990	2005	2015	2016	2017	2018	2019
Exploration	4.6	12.0	1.3	0.9	1.7	1.2	0.8
Production	61.8	85.2	96.9	94.1	96.6	100.6	104.7
Processing	49.7	30.4	32.0	33.2	34.5	35.2	37.2
Transmission and Storage	57.4	36.2	34.4	34.8	32.9	35.3	38.2
Distribution	45.5	25.6	14.4	14.3	14.2	14.1	14.0
Total	219.0	189.4	179.0	177.4	179.9	186.4	194.9

Note: Totals may not sum due to independent rounding.

Table 3-63: CH₄ Emissions from Natural Gas Systems (MMT CO₂ Eq.)[a]

Stage	1990	2005	2015	2016	2017	2018	2019
Exploration[b]	4.2	10.3	1.0	0.7	1.2	0.8	0.5
Production	58.8	80.4	89.3	86.6	89.4	90.8	93.7

	1990		2005		2015	2016	2017	2018	2019
Onshore Production	36.0		54.9		52.1	49.5	50.7	51.7	52.0
Gathering and Boosting[c]	18.5		23.9		36.6	36.3	38.0	38.3	40.9
Offshore Production	4.3		1.8		0.6	0.8	0.7	0.8	0.8
Processing	**21.3**		**11.6**		**11.0**	**11.2**	**11.5**	**12.1**	**12.4**
Transmission and Storage	**57.2**		**36.1**		**34.1**	**34.5**	**32.4**	**34.8**	**37.0**
Distribution	**45.5**		**25.6**		**14.3**	**14.3**	**14.2**	**14.1**	**14.0**
Total	**186.9**		**164.2**		**149.8**	**147.3**	**148.7**	**152.5**	**157.6**

Note: Totals may not sum due to independent rounding.

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

[b] Exploration includes well drilling, testing, and completions.

[c] Gathering and boosting includes gathering and boosting station routine vented and leak sources, gathering pipeline leaks and blowdowns, and gathering and boosting station episodic events.

Table 3-64: CH_4 Emissions from Natural Gas Systems (kt)[a]

Stage	1990		2005		2015	2016	2017	2018	2019
Exploration[b]	**167**		**412**		**42**	**28**	**49**	**33**	**21**
Production	**2,350**		**3,227**		**3,572**	**3,466**	**3,574**	**3,631**	**3,748**
Onshore Production	1,441		2,197		2,085	1,981	2,026	2,068	2,081
Gathering and Boosting[c]	739		957		1,463	1,453	1,521	1,532	1,636
Offshore Production	170		73		24	32	26	31	31
Processing	**853**		**463**		**440**	**448**	**460**	**483**	**497**
Transmission and Storage	**2,288**		**1,443**		**1,366**	**1,379**	**1,298**	**1,390**	**1,478**
Distribution	**1,819**		**1,023**		**574**	**573**	**569**	**565**	**560**
Total	**7,478**		**6,567**		**5,994**	**5,894**	**5,949**	**6,101**	**6,305**

Note: Totals may not sum due to independent rounding.

[a] These values represent CH_4 emitted to the atmosphere. CH_4 that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

[b] Exploration includes well drilling, testing, and completions.

[c] Gathering and boosting includes gathering and boosting station routine vented and leak sources, gathering pipeline leaks and blowdowns, and gathering and boosting station episodic events.

Table 3-65: Non-combustion CO_2 Emissions from Natural Gas Systems (MMT)

Stage	1990		2005		2015	2016	2017	2018	2019
Exploration	0.4		1.7		0.3	0.2	0.4	0.4	0.2
Production	3.0		4.5		7.6	7.5	7.3	9.8	11.0
Processing	28.3		18.8		21.0	22.0	23.0	23.1	24.8
Transmission and Storage	0.2		0.2		0.2	0.3	0.5	0.5	1.2
Distribution	0.1		+		+	+	+	+	+
Total	**32.0**		**25.2**		**29.1**	**30.1**	**31.2**	**33.9**	**37.2**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 3-66: Non-combustion CO_2 Emissions from Natural Gas Systems (kt)

Stage	1990		2005		2015	2016	2017	2018	2019
Exploration	421		1,651		282	193	445	355	236
Production	3,048		4,486		7,623	7,482	7,261	9,841	10,951
Processing	28,338		18,836		20,977	22,022	22,980	23,126	24,786
Transmission and Storage	181		176		228	339	498	546	1,244
Distribution	54		30		17	17	17	17	16
Total	**32,042**		**25,179**		**29,127**	**30,054**	**31,200**	**33,885**	**37,234**

Note: Totals may not sum due to independent rounding.

Table 3-67: N₂O Emissions from Natural Gas Systems (Metric Tons CO₂ Eq.)

Stage	1990	2005	2015	2016	2017	2018	2019
Exploration	458	1,348	3,248	115	244	2,267	123
Production	4,359	5,804	9,835	8,892	4,453	5,094	5,591
Processing	NO	3,348	5,766	3,819	3,066	3,587	4,987
Transmission and Storage	257	309	346	382	462	234	630
Distribution	NO	NO	NO	NO	NO	NO	NO
Total	**5,073**	**10,808**	**19,196**	**13,209**	**8,226**	**11,182**	**11,331**

Note: Totals may not sum due to independent rounding.
NO (Not Occurring)

Table 3-68: N₂O Emissions from Natural Gas Systems (Metric Tons N₂O)

Stage	1990	2005	2015	2016	2017	2018	2019
Exploration	1.5	4.5	10.9	0.4	0.8	7.6	0.4
Production	14.6	19.5	33.0	29.8	14.9	17.1	18.8
Processing	NO	11.2	19.3	12.8	10.3	12.0	16.7
Transmission and Storage	0.9	1.0	1.2	1.3	1.6	0.8	2.1
Distribution	NO	NO	NO	NO	NO	NO	NO
Total	**17.0**	**36.3**	**64.4**	**44.3**	**27.6**	**37.5**	**38.0**

Note: Totals may not sum due to independent rounding.
NO (Not Occurring)

Methodology

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's Greenhouse Gas Reporting Program (GHGRP) that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas system emission estimates in the Inventory, which involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources (i.e., equipment types or processes), and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and emission reduction data to calculate net emissions. The estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

Emission Factors. Key references for emission factors for CH_4 and CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), the EPA's GHGRP (EPA 2020), and others.

The 1996 GRI/EPA study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating segments of the U.S. natural gas system. The GRI/EPA study was based on a combination of process engineering studies, collection of activity data, and measurements at representative natural gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy's Energy Information Administration (EIA) annual gross production data for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition of natural gas for each NEMS region.

GHGRP Subpart W data were used to develop CH_4, CO_2, and N_2O emission factors for many sources in the Inventory. In the exploration and production segments, GHGRP data were used to develop emission factors used for all years of the time series for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, miscellaneous flaring, gathering and boosting pipelines, and certain sources at gathering and boosting stations. In the processing segment, for recent years of the times series, GHGRP data were used to develop emission factors for leaks, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, GHGRP data were used to develop factors for all years of the time series for LNG stations and terminals and transmission pipeline blowdowns, and for pneumatic controllers for recent years of the times series.

Other data sources used for CH_4 emission factors include Zimmerle et al. (2015) for transmission and storage station leaks and compressors, GSI (2019) for underground storage well leaks, GTI (2009 and 2019) for commercial and industrial meters, Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations, Zimmerle et al. (2019) for gathering and boosting stations, and Bureau of Ocean Energy Management (BOEM) reports.

For CO_2 emissions from sources in the exploration, production and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors.

Flaring N_2O emissions were estimated for flaring sources using GHGRP data.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4, CO_2, and N_2O emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP (EPA 2020); Enverus (Enverus 2020); BOEM; Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR Program annual data; Oil and Gas Journal; and PHMSA.

For a few sources, recent direct activity data are not available. For these sources, either 2018 data were used as a proxy for 2019 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information, and take into account regulatory and voluntary reductions. However, for production and transmission and storage, some sources are calculated using potential emission factors, and the step of deducting CH_4 that is not emitted from the total CH_4 potential estimates to develop net CH_4 emissions is applied. To take into account use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the Inventory are those reported to Natural Gas STAR for certain sources.

Through EPA's stakeholder process on oil and gas in the Inventory, EPA received stakeholder feedback on updates under consideration for the Inventory. Stakeholder feedback is noted below in Recalculations Discussion and Planned Improvements.

The United States reports data to the UNFCCC using this Inventory report along with Common Reporting Format (CRF) tables. This note is provided for those reviewing the CRF tables: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRF table 1.B.2. Disaggregating flaring and venting estimates across the

Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty and Time-Series Consistency

EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize the uncertainty for natural gas systems. For more information on the approach, please see the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates (2018 Uncertainty Memo).*[86]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from natural gas systems for the current Inventory. Uncertainty estimates for N_2O were not developed given the minor contribution of N_2O to emission totals. For the CH_4 uncertainty analysis, EPA focused on the 14 highest-emitting sources for the year 2019, which together emitted 75 percent of methane from natural gas systems in 2019, and extrapolated the estimated uncertainty for the remaining sources. Uncertainty was not previously estimated specifically for CO_2 emissions, instead the uncertainty bounds calculated for CH_4 were applied to CO_2 emissions estimates. As part of the stakeholder process for the current Inventory, EPA developed an update to the uncertainty analysis for CO_2. The update is documented in the memorandum, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates.*[87] EPA ultimately applied the same approach as was developed for CH_4. For the CO_2 uncertainty analysis, EPA focused on the 3 highest-emitting sources for the year 2018 (from the previous 1990-2018 Inventory), which together emitted 82 percent of CO_2 from natural gas systems in 2018, and extrapolated the estimated uncertainty for the remaining sources. The CO_2 uncertainty calculations were developed as part of the stakeholder process and were based on the previous 1990-2018 Inventory; as a result, the uncertainty results from last year's Inventory for year 2018 are applied for this year's uncertainty analysis. In future years, the CO_2 uncertainty bounds will be calculated using the most recent Inventory data. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2019, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-69. Natural gas systems CH_4 emissions in 2019 were estimated to be between 133.4 and 180.1 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems CO_2 emissions in 2019 were estimated to be between 31.3 and 44.3 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time

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[86] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

[87] Stakeholder materials, including draft and final memoranda for the current (i.e. 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

series (e.g., liquids unloading with plunger lifts and reduced emissions completions were not used early in the time series and cast iron distribution mains were more prevalent than plastic mains in early years). Transmission and gas processing compressor leak and vent emissions were also higher in the early years of the time series.

Table 3-69: Approach 2 Quantitative Uncertainty Estimates for CH₄ and Non-combustion CO₂ Emissions from Natural Gas Systems (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH₄	157.6	133.4	180.1	-15%	+14%
Natural Gas Systems	CO₂	37.2	31.3	44.3	-16%	19%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2019 CH₄ and year 2018 CO₂ emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-63 and Table 3-64.

GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The natural gas systems emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[88]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder webinars in September and November of 2020. EPA released memos detailing updates under consideration and requesting stakeholder feedback.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or

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[88] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed and in many cases, incorporated data from these data sources. The second type of study can provide general indications of potential over- and under-estimates.

One comment on the public review draft suggested that the inventory estimates be compared with an observational analysis from a 2019 Lan et al. study.[89] Lan et al. estimated an average increasing trend of U.S. oil and gas methane emissions of 3.4 percent +/-1.4 percent per year between 2006 and 2015, based on three U.S. measurement sites that were "substantially influenced by O&NG activities." This study did not address the magnitude of emissions. Nationally, in the Inventory, methane emissions from oil and gas decreased by an average of 1 percent per year from 2006 to 2015, largely driven by the natural gas distribution and transmission and storage segments. A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the Inventory and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level Inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[90] The gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[91] An updated version of the gridded inventory is being developed and will improve efforts to compare results of the Inventory with atmospheric studies.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. In September and November 2020, EPA released draft memoranda that discussed changes under consideration, and requested stakeholder feedback on those changes. EPA then created updated versions of the memoranda to document the methodology implemented in the current Inventory.[92] Memoranda cited in the Recalculations Discussion below are: *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas Customer Meter Emissions* (*Customer Meters* memo) and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Produced Water Emissions* (*Produced Water* memo).

EPA thoroughly evaluated relevant information available and made several updates to the Inventory, including using revised emission factors and produced water volumes to calculate produced water emissions, and using GTI 2019 along with GTI 2009 study data to calculate customer meter emissions. These changes are discussed in detail below. In addition, certain sources did not undergo methodological updates, but CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2018 to the current (recalculated) estimate for 2018. For sources without methodological updates, the emissions changes were mostly due to GHGRP data submission revisions and updates to well counts in the Enverus dataset.

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[89] See <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2018GL081731>.

[90] See <https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions>.

[91] See <https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014>.

[92] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

The combined impact of revisions to 2018 natural gas sector CH_4 emissions, compared to the previous Inventory, is an increase from 140.0 to 152.5 MMT CO_2 Eq. (12.6 MMT CO_2 Eq., or 9 percent). The recalculations resulted in an average increase in CH_4 emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 6.6 MMT CO_2 Eq., or 4 percent.

The combined impact of revisions to 2018 natural gas sector CO_2 emissions, compared to the previous Inventory, is a decrease from 35.0 MMT to 33.9 MMT, or 3 percent. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 0.1 MMT CO_2 Eq., or 0.5 percent.

The combined impact of revisions to 2018 natural gas sector N_2O emissions, compared to the previous Inventory, is an increase from 10.4 kt CO_2 Eq. to 11.2 kt CO_2 Eq., or 8 percent. The recalculations resulted in an average increase in emission estimates across the 1990 through 2018 time series, compared to the previous Inventory, of 6 percent.

In Table 3-70 and Table 3-71 below are categories in Natural Gas Systems with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2018 to the current (recalculated) estimate for 2018. No changes made to N_2O estimates resulted in a change greater than 0.05 MMT CO_2 Eq. For more information, please see the Recalculations Discussion below.

Table 3-70: Recalculations of CO_2 in Natural Gas Systems (MMT CO_2)

Segment and Emission Source	Previous Estimate Year 2018, 2020 Inventory	Current Estimate Year 2018, 2021 Inventory	Current Estimate Year 2019, 2021 Inventory
Exploration	*0.4*	**0.4**	**0.2**
HF Gas Well Completions	*0.4*	0.3	0.2
Production	*9.6*	**9.8**	**11.0**
Gathering Stations Flares Stacks	*4.2*	4.4	5.0
Processing	*24.5*	**23.1**	**24.8**
AGR Vents	*17.5*	16.7	16.5
Flares	*7.0*	6.4	8.3
Transmission and Storage	*0.5*	**0.5**	**1.2**
LNG Export Terminals	*0.3*	0.3	1.0
Distribution	+	**+**	**+**
Customer Meters	+	+	+
Total	*35.0*	**33.9**	**37.2**

+ Does not exceed 0.05 MMT CO_2.

Table 3-71: Recalculations of CH_4 in Natural Gas Systems (MMT CO_2 Eq.)

Segment and Emission Source	Previous Estimate Year 2018, 2020 Inventory	Current Estimate Year 2018, 2021 Inventory	Current Estimate Year 2019, 2021 Inventory
Exploration	*1.1*	**0.8**	**0.5**
HF Gas Well Completions	*1.0*	0.8	0.5
Non-HF Gas Well Completions	*0.1*	+	+
Production	*80.9*	**90.8**	**93.7**
Produced Water (Onshore Production)	*1.5*	4.7	4.7
G&B Station Sources	*31.4*	35.0	37.3
Pneumatic Controllers (Onshore Production)	*25.4*	26.9	28.2
Liquids Unloading	*4.4*	5.1	4.4
HF Workovers	*0.6*	0.5	0.4
Chemical Injection Pumps	2.7	2.9	2.8
Kimray Pumps	1.8	1.9	1.8
Gas Engines	6.2	6.4	6.3
Compressors	1.6	1.7	1.7

Processing	*12.2*	**12.1**	**12.4**
Reciprocating Compressors	*1.6*	1.5	1.2
Transmission and Storage	*33.9*	**34.8**	**37.0**
Reciprocating Compressors (Transmission)	*9.2*	9.3	10.2
Pneumatic Controllers (Storage)	*+*	0.6	0.6
Distribution	*11.8*	**14.1**	**14.0**
Customer Meters	*1.4*	3.7	3.7
Total	*140.0*	**152.5**	**157.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Exploration

HF Gas Well Completions (Recalculation with Updated Data)

HF gas well completions CH_4 emissions estimates averaged no change across the time series. However, emissions decreased by 18 percent in 2018, compared to the previous Inventory, with the largest change being in RECs with Venting. These changes were due to GHGRP submission revisions.

Table 3-72: HF Gas Well Completions National Emissions (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
HF Completions - Non-REC with Venting	156,988		382,619		924	1,109	2,932	1,085	641
HF Completions - Non-REC with Flaring	2,223		6,828		394	75	476	621	335
HF Completions - REC with Venting	0		6,489		14,463	12,569	37,650	28,934	17,827
HF Completions - REC with Flaring	0		1,855		8,760	4,581	5,656	1,344	1,139
Total Emissions	**159,211**		**397,791**		**24,541**	**18,334**	**46,713**	**31,984**	**19,942**
Previous Estimate	*153,924*		*397,427*		*24,566*	*18,177*	*47,414*	*39,036*	*NA*

NA (Not Applicable)

HF gas well completion CO_2 emissions estimates decreased by an average of approximately 1 percent across the time series and decreased by 26 percent in 2018, compared to the previous Inventory, primarily due to decreases in emissions from RECs with Flaring. These changes were due to GHGRP submission revisions.

Table 3-73: HF Gas Well Completions National Emissions (kt CO$_2$)

Source	1990		2005		2015	2016	2017	2018	2019
HF Completions - Non-REC with Venting	11		26		0.2	+	0.4	+	+
HF Completions - Non-REC with Flaring	402		1,236		49	12	37	54	32
HF Completions - REC with Venting	0		3		1	0	1	3	0
HF Completions - REC with Flaring	0		370		218	167	398	233	198
Total Emissions	**413**		**1,634**		**268**	**179**	**436**	**290**	**230**
Previous Estimate	*399*		*1,633*		*268*	*177*	*449*	*392*	*NA*

+ Does not exceed 0.05 kt CO$_2$

NA (Not Applicable)

Non-HF Gas Well Completions (Recalculation with Updated Data)

Non-HF gas well completion CH$_4$ emissions estimates decreased by an average of 3 percent across the time series and decreased by 82 percent in 2018, compared to the previous inventory. These changes were due to GHGRP submission revisions and a correction to the Inventory calculations of the number of non-HF completions that were vented versus flared in 2018.

Table 3-74: Non-HF Gas Well Completions National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Non-HF Completions - Vented	5,747		10,925		14,872	8,602	850	272	832
Non-HF Completions - Flared	20		38		40	82	714	481	0
Total Emissions	**5,767**		**10,963**		**14,912**	**8,684**	**1,564**	**753**	**832**
Previous Estimate	*5,717*		*10,252*		*13,667*	*8,077*	*1,440*	*4,285*	*NA*

NA (Not Applicable)

Production

Produced Water (Methodological Update)

EPA updated the calculation methodology for produced water to estimate emissions for all produced water from natural gas wells. Previous inventories only estimated emissions for two CBM formations (i.e., Powder River in Wyoming and Black Warrior in Alabama). The updated methodology includes updates to the produced water quantities and the emission factor, each of which are discussed here. EPA's considerations for this source are documented in the *Produced Water* Memo.[93]

Produced water quantities (i.e., bbl) from natural gas wells were obtained for 36 natural gas-producing states as described below:

- Produced water quantities for 1990-2018 were obtained using DrillingInfo and Prism datasets from Enverus for 29 states (i.e., AK, AL, AR, AZ, CA, CO, FL, ID, KY, LA, MD, MI, MN, MO, MS, MT, NC, ND, NE, NM, NV, NY, OR, SD, TN, TX, UT, VA, and WY) (Enverus 2021). Linear interpolation was used to correct an obviously inaccurate new-zero produced water quantity value in Colorado for 1998.
- For four additional states, produced water quantities for 1990-2018 were available on state agency websites– KS (Kansas Department of Health and Environment 2020), OH (Ohio Environmental Protection

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[93] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

Agency 2020), OK (Oklahoma Department of Environmental Quality 2020), and PA (Pennsylvania Department of Environmental Protection 2020). Produced water quantities for 2018 were used as proxy data for 2019 for these four states.

- Produced water quantities for 1990-2018 were estimated for three states (IL, IN, and WV) using state-level produced water production ratios for gas wells. Well-level produced water data for gas wells for 2011 were obtained from the DrillingInfo dataset (Enverus 2021) and gas production data were obtained from state agency websites – IL (Illinois Office of Oil and Gas Resource Management 2020), IN (Indiana Division of Oil & Gas 2020), and WV (West Virginia Department of Environmental Protection 2020). Using these well-level produced water data and the gas production data, production ratios were developed for gas wells in each state. These production ratios were then applied to annual state-level gas production data (2000-2019) from EIA (EIA 2020). Produced water quantities for 2018 were used as proxy data for 2019 for these three states.

EPA updated the produced water EF to use an EF consistent with the Production Module of the 2017 Oil and Gas Tool,[94] and applied this EF to all gas well produced water (EPA 2017). Overall, the update increases the emission estimate for produced water (now including all gas production), by approximately three times in recent years, compared to the previous Inventory.

EPA received feedback on this update through its September 2020 memo and through the public review draft of the inventory.

A stakeholder indicated that the typical practice is to route produced water to a tank battery, once it reaches the surface and has been separated from the oil and gas. A stakeholder requested that data from the latest 2017 Ground Water Protection Council produced water management practices survey be used to determine the percent of produced water that is stored in tanks. The stakeholder indicated that approximately 16 percent of produced water has the potential of being stored in a tank battery that could potentially flash (based on the 2012 Ground Water Protection Council produced water management practices survey). After further assessment of the 2012 and 2017 water management practice surveys, EPA maintained the assumption that all produced water goes through tanks and emissions are flashed, consistent with the approach used for the public review draft of the Inventory.

A stakeholder commented that current regulations under 40 CFR 60 subpart OOOOa require that certain storage vessels route emission vapors to a recovery device, flare, or other control device. EPA currently does not have specific data to address the use of controls on produced water tanks but will continue to assess this issue in future inventories should additional data become available.

Table 3-75: Produced Water National CH$_4$ Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Gas Well Produced Water	82,250		139,453		171,523	154,394	157,488	188,601	187,070
Previous Estimate	*2,767*		*59,884*		*60,745*	*61,673*	*61,673*	*61,673*	*61,673*

NA (Not Applicable)

Gathering and Boosting (G&B) Stations (Recalculation with Updated Data)

Methane emission estimates for sources at gathering and boosting stations increased in the current Inventory by an average of 2 percent across the time series and increased by 11 percent in 2018, compared to the previous Inventory. The G&B sources with the largest increase in CH$_4$ emissions estimates for year 2018 are tanks (increase of 70 kt, or 39 percent), gas engines (increase of 19 kt, or 5 percent), and station blowdowns (increase of 17 kt or 27 percent). These changes were due to GHGRP submission revisions.

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[94] *Instructions for Using the 2017 EPA Nonpoint Oil and Gas Emissions Estimation Tool, Production Module*. Produced by Eastern Research Group, Inc. (ERG) for U.S. Environmental Protection Agency. October 2019.

Flare stack CO_2 emissions at G&B stations increased in the current inventory by an average of 0.6 percent, compared to the previous Inventory. These changes were due to GHGRP submission revisions.

Table 3-76: Gathering Stations Sources National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2015	2016	2017	2018	2019
Compressors	130,744	165,028	261,792	260,325	278,692	296,279	309,465
Tanks	131,152	165,543	262,610	261,139	255,244	251,243	301,338
Station Blowdowns	20,715	26,148	41,479	41,247	63,833	78,550	68,773
Dehydrator Vents - Large units	36,022	45,468	72,128	71,724	61,297	56,932	55,218
High-bleed Pneumatic Devices	17,466	22,046	34,973	34,777	33,985	24,599	23,624
Intermittent Bleed Pneumatic Devices	80,265	101,312	160,716	159,816	178,037	163,253	170,952
Low-Bleed Pneumatic Devices	2,784	3,515	5,575	5,544	5,877	5,803	6,819
Gas Engines	173,040	218,415	346,483	344,542	369,192	392,459	410,376
Other Gathering Sources	60,349	69,352	120,838	120,161	113,470	129,876	145,139
Total Emissions	**652,538**	**823,648**	**1,306,595**	**1,299,276**	**1,359,628**	**1,398,994**	**1,491,704**
Previous Estimate	*641,624*	*815,454*	*1,293,262*	*1,281,711*	*1,281,484*	*1,257,799*	*NA*

NA (Not Applicable)

Table 3-77: Gathering Stations Flare Stacks National CO_2 Emissions (Metric Tons CO_2)

Source	1990	2005	2015	2016	2017	2018	2019
Flare Stacks	1,367,178	1,725,682	2,737,537	2,722,202	2,317,495	4,386,761	5,005,631
Previous Estimate	*1,354,751*	*1,721,783*	*2,730,646*	*2,706,255*	*2,300,171*	*4,205,760*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Recalculation with Updated Data)

Pneumatic controller CH_4 emission estimates increased in the current Inventory by an average of 3.9 percent across the time series, compared to the previous Inventory. This change was due to GHGRP submission revisions which increased the number of intermittent bleed controllers and updates to well counts in the Enverus dataset.

Table 3-78: Production Segment Pneumatic Controller National Emissions (Metric Tons CH_4)

Source	1990	2005	2015	2016	2017	2018	2019
Low Bleed	0	24,049	33,107	32,610	35,856	35,671	33,538
High Bleed	291,948	481,227	106,286	107,714	112,764	92,886	74,565
Intermittent Bleed	190,386	557,410	979,719	923,468	954,461	947,089	1,018,428
Total Emissions	**482,334**	**1,062,685**	**1,119,112**	**1,063,791**	**1,103,082**	**1,075,645**	**1,126,531**
Previous Estimate	*490,594*	*1,023,770*	*1,072,732*	*1,037,136*	*1,062,086*	*1,016,357*	*NA*

NA (Not Applicable)

Liquids Unloading (Recalculation with Updated Data)

Liquids unloading CH_4 emission estimates increased for 2018 by 15 percent in the current Inventory, compared to the previous Inventory. Compared to the previous Inventory, on average across the time series, liquids unloading

CH$_4$ emission estimates increased more than 2 percent. These changes were due to GHGRP submission revisions and updates to well counts in the Enverus dataset.

Table 3-79: Liquids Unloading National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Unloading with Plunger Lifts	NO		127,621		65,375	61,359	60,724	83,841	76,937
Unloading without Plunger Lifts	355,840		250,973		102,166	84,096	90,767	120,146	98,892
Total Emissions	**355,840**		**378,594**		**167,540**	**145,455**	**151,492**	**203,987**	**175,828**
Previous Estimated Emissions	*371,391*		*372,614*		*160,061*	*127,663*	*129,790*	*177,298*	*NA*

NO (Not Occurring)
NA (Not Applicable)

HF Gas Well Workovers (Recalculation with Updated Data)

HF gas well workover CH$_4$ emissions decreased an average of 1 percent across the time series and decreased by 16 percent in 2018, when comparing the current Inventory to the previous Inventory, mostly due to decreases in emissions from RECs with Venting. These changes were due to GHGRP submission revisions.

Table 3-80: HF Gas Well Workovers National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
HF Workovers - Non-REC with Venting	25,774		60,903		1,752	7,530	8,638	1,394	4,301
HF Workovers - Non-REC with Flaring	365		953		80	72	521	1,094	606
HF Workovers - REC with Venting	NO		576		8,685	6,384	16,146	18,010	8,824
HF Workovers - REC with Flaring	NO		4		1,695	1,234	4,885	39	257
Total Emissions	**26,139**		**62,437**		**12,212**	**15,220**	**30,190**	**20,537**	**13,988**
Previous Estimate	*26,139*		*62,437*		*12,175*	*15,155*	*31,485*	*24,422*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engine (combustion slip) CH$_4$ emissions increased an average of 5 percent across the time series, compared to the previous Inventory. These changes were due to updates to well counts in the Enverus dataset.

Table 3-81: Gas Engine National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Gas Engines	116,684		129,715		132,093	124,835	120,272	116,437	111,886
Previous Estimate	*116,558*		*123,713*		*125,843*	*119,100*	*114,599*	*110,432*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH$_4$ emissions estimates increased an average of 4 percent across the time series, compared to the previous Inventory. These changes were due to updates to well counts in the Enverus dataset.

Table 3-82: Chemical Injection Pump National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019

Source	1990		2005		2015	2016	2017	2018	2019
Chemical Injection Pumps	26,060		87,007		117,857	116,038	115,322	114,636	112,843
Previous Estimate	*26,323*		*83,687*		*113,336*	*113,243*	*111,421*	*109,376*	*NA*

NA (Not Applicable)

Kimray Pumps (Recalculation with Updated Data)

CH$_4$ emissions from Kimray pumps decreased by an average of 2 percent across time series, compared to the previous Inventory. These changes were due to updates to well counts in the Enverus dataset.

Table 3-83: Kimray Pumps National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Kimray Pumps	141,304		110,923		76,818	75,485	75,042	74,596	73,426
Previous Estimate	*148,064*		*114,936*		*73,850*	*73,660*	*72,475*	*71,125*	*NA*

NA (Not Applicable)

Compressors (Recalculation with Updated Data)

Compressors CH$_4$ emissions estimates increased an average of 1 percent across the time series, compared to the previous Inventory. These changes were due to updates to well counts in the Enverus dataset.

Table 3-84: Compressors National Emissions (Metric Tons CH$_4$)

Source	1990		2005		2015	2016	2017	2018	2019
Compressors	28,189		56,528		70,121	68,904	68,500	68,093	67,025
Previous Estimate	*28,645*		*55,520*		*67,412*	*67,239*	*66,157*	*64,925*	*NA*

NA (Not Applicable)

Well Counts (Recalculation with Updated Data)

EPA uses annual producing gas well counts as an input for estimates of emissions from multiple sources in the Inventory, including exploration well testing, pneumatic controllers, chemical injection pumps, well workovers, and equipment leaks. Annual well count data are obtained from Enverus for the entire time series during each Inventory cycle, and a new data processing methodology was implemented this year due to a restructuring of the Enverus well count data (Enverus 2021). Due to the data restructuring and the new processing methodology, annual gas well counts increased by an average of 1 percent across the 1990-2018 time series and increased by 5 percent in 2018, compared to the previous Inventory.

Table 3-85: National Gas Well Counts

Source	1990		2005		2015	2016	2017	2018	2019
Gas Wells	185,141		351,982		436,432	429,697	427,046	424,507	417,866
Previous Estimate	*193,232*		*346,484*		*419,692*	*419,346*	*412,601*	*405,026*	*NA*

NA (Not Applicable)

In December 2020, EIA released an updated time series of national oil and gas well counts (covering 2000 through 2018). EIA estimates 969,136 total producing wells for year 2019. EPA's total well count for this year is 939,637. EPA's well counts are generally lower than EIA's (e.g., around 3 percent lower in 2019). EIA's well counts include side tracks (i.e., secondary wellbore away from original wellbore in order to bypass unusable formation, explore nearby formations, or other reasons) completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. EPA and EIA use a different threshold for distinguishing between oil versus gas (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells

(e.g., 44 percent versus EPA's 56 percent in 2019) and a higher fraction of gas wells (e.g., 56 percent versus EPA's 44 percent in 2019) than EPA.

Processing

Acid Gas Removal (Recalculation with Updated Data)

Acid gas removal unit (AGR) CO_2 emission estimates decreased by less than 1 percent across the time series, compared to the previous Inventory. The 2018 estimate decreased by 4 percent when compared to the previous inventory. These changes are due to GHGRP submission revisions.

Table 3-86: AGR National CO_2 Emissions (kt CO_2)

Source	1990		2005		2015	2016	2017	2018	2019
Acid Gas Removal	28,282		15,281		14,878	16,741	17,218	16,699	16,498
Previous Estimate	*28,282*		*15,339*		*14,979*	*16,679*	*17,182*	*17,451*	*NA*

NA (Not Applicable)

Flares (Recalculation with Updated Data)

Processing segment flare CO_2 emission estimates decreased by less than 1 percent across the 1993 to 2018 time series in the current Inventory. Processing segment flare CO_2 emission estimates decreased by approximately 8 percent for 2018 in the current Inventory, compared to the previous Inventory. These changes are due to GHGRP submission revisions.

Table 3-87: Processing Segment Flares National Emissions (kt CO_2)

Source	1990		2005		2015	2016	2017	2018	2019
Flares	NO		3,517		6,057	5,246	5,726	6,394	8,257
Previous Estimate	*NO*		*3,515*		*6,054*	*5,195*	*5,679*	*6,981*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Reciprocating Compressors (Recalculation with Updated Data)

Reciprocating compressor CH_4 emission estimates decreased by less than 1 percent on average for 2011 to 2018 in the current Inventory and decreased by 5 percent for 2018 in the current Inventory, compared to the previous Inventory. This decrease in the CH_4 emission estimates is due to GHGRP submission revisions.

Table 3-88: Processing Segment Reciprocating Compressors National Emissions (Metric Tons CH_4)

Source	1990		2005		2015	2016	2017	2018	2019
Reciprocating Compressors	324,939		NA		67,988	63,565	64,789	59,373	46,652
Previous Estimate	*324,939*		*NA*		*67,982*	*63,682*	*64,955*	*62,574*	*NA*

NA (Not Applicable)

Transmission and Storage

There were no methodological updates to the transmission and storage segment, but there were recalculations due to updated data that resulted in an average increase in calculated emissions over the time series from this segment of 0.19 MMT CO_2 Eq. of CH_4 (or 0.5 percent) and less than 0.01 MMT CO_2 (or 2 percent).

Transmission Station Reciprocating Compressors (Recalculation with Updated Data)

Methane emission estimates from reciprocating compressors at transmission compressor stations increased by an average of 0.2 percent for 2011 to 2018, compared to the previous Inventory. This increase in the CH_4 emission estimates is due to GHGRP submission revisions.

Table 3-89: Transmission Station Reciprocating Compressors National Emissions (Metric Tons CH_4)

Source	1990	2005	2015	2016	2017	2018	2019
Transmission Station – Reciprocating Compressors	NO	NO	341,316	345,224	347,830	373,233	406,453
Previous Estimate	*NO*	*NO*	*341,316*	*345,224*	*346,527*	*369,976*	*NA*

NO (Not Occurring)
NA (Not Applicable)

Storage Pneumatic Controllers (Recalculation with Updated Data)

Storage segment pneumatic controller CH_4 emission estimates increased in the current Inventory for 2014-2018, compared to the previous Inventory. Emission estimates for 2018 increased by 24,169 metric tons CH_4, compared to the previous Inventory. This increase in the CH_4 emission estimates is due to GHGRP submission revisions.

Table 3-90: Storage Segment Pneumatic Controller National Emissions (Metric Tons CH_4)

Source	1990	2005	2015	2016	2017	2018	2019
Low Bleed	NE	NE	15,902	19,904	20,465	17,291	17,187
High Bleed	NE	NE	5,734	5,648	6,419	6,485	6,365
Intermittent Bleed	NE	NE	401	413	480	535	516
Total Emissions	**44,441**	**35,263**	**22,038**	**25,965**	**27,364**	**24,310**	**24,067**
Previous Estimate	*44,441*	*35,263*	*22,094*	*1,402*	*27,364*	*141*	*NA*

NE (Not Estimated)
NA (Not Applicable)

LNG Export Terminals (Recalculation with Updated Data)

LNG export terminal CO_2 emissions estimates for equipment leaks, compressors, and flares increased by 20 percent in 2018, compared to the previous Inventory. This increase in the CO_2 emission estimate for 2018 is due to GHGRP submission revisions.

Table 3-91: LNG Export Terminal National Emissions (Metric Tons CO_2)

Source	1990	2005	2015	2016	2017	2018	2019
LNG Export Terminals (eq. leaks, compressors, flares)	23	23	23	97,935	277,979	327,535	979,142
Previous Estimate	*23*	*23*	*23*	*97,935*	*277,979*	*273,956*	*NA*

NA (Not Applicable)

Distribution

Customer Meters (Methodological Update)

EPA updated the commercial and industrial meters methodologies to use leak data from the GTI 2009 and GTI 2019 studies. The GTI 2019 study measured CH_4 emissions rates at commercial and industrial meters in six regions across the country and calculated population EFs for each meter type. The GTI 2009 study conducted similar measurements and was used to calculate emissions for commercial and industrial meters in the previous (1990 to 2018) Inventory. EPA applied weighted average population EFs from the two studies across the time series for the methodology implemented in the Inventory. The *Customer Meters memo* provides details on the methodology implemented into the final inventory.

Commercial and industrial meter CH_4 and CO_2 emissions increased by an average of 173 percent across the time series, compared to the previous Inventory. The increase in both CH_4 and CO_2 emissions is due to differences in the EFs used in the current Inventory and the previous Inventory. The previous inventory used a lower EF (based on commercial meter measurements only) and applied that EF to both commercial and industrial meter counts. The updated methodology uses commercial meter data from both the 2009 and 2019 GTI studies to develop an EF that is applied to commercial meter counts, and uses industrial meter data from both the 2009 (leak emissions only) and GTI 2019 studies to develop an EF that is applied to industrial meter counts. No change was made to the activity data approach.

EPA received comments on the September 2020 version of the *Customer Meters* Memo and through the public review draft of the Inventory. These comments included a recommendation to delay updates until additional data could be collected. The comments also recommended using separate EFs for commercial and industrial meters and region-specific EFs. The largest source of emissions from customer meters in the 2009 study was vented emissions from industrial meters, with an average emission factor per meter of 3,487 kg/year, compared with an average emission factor per industrial meter from leaks of 105 kg/year. Venting emissions were observed and measured at 2 out of the 6 companies participating in the 2009 GTI study. This source of emissions was not studied in the 2019 GTI study. The final methodology for industrial meters uses an EF calculated only from leak emissions, which have less variability, and does not include the more limited and highly variable vented emissions. EPA did not use region-specific EFs due to the limited data available for each region, but did finalize separate EFs for commercial and industrial meters that rely on the leak emissions from the 2009 and 2019 GTI studies. Using data from both studies to calculate population EFs greatly increases the number of data points that serve as the basis of the EFs, instead of only using the commercial meter EF from the 2009 GTI study. EPA seeks stakeholder feedback on upcoming or ongoing research studies that measure vented emissions from industrial meters.

Table 3-92: Commercial and Industrial Meter National Emissions (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
Commercial Meters	99,129		121,634		127,615	128,108	128,698	129,130	129,796
Industrial Meters	22,926		21,653		19,775	19,828	19,419	19,426	19,239
Total	**122,055**		**143,287**		**147,390**	**147,936**	**148,118**	**148,555**	**149,036**
Previous Estimate	*43,362*		*52,605*		*54,919*	*55,129*	*55,324*	*56,140*	*NA*

NA (Not Applicable)

Table 3-93: Commercial and Industrial Meter National Emissions (Metric Tons CO₂)

Source	1990		2005		2015	2016	2017	2018	2019
Commercial Meters	2,919		3,581		3,757	3,772	3,789	3,802	3,822
Industrial Meters	675		638		582	584	572	572	566
Total	**3,594**		**4,219**		**4,340**	**4,356**	**4,361**	**4,374**	**4,388**
Previous Estimate	*1,277*		*1,549*		*1,617*	*1,623*	*1,629*	*1,653*	*NA*

NA (Not Applicable)

Planned Improvements

EPA seeks stakeholder feedback on the improvements noted below.

Post-Meter Fugitive Emissions

The Inventory does not currently include estimates for post-meter fugitive (leakage) emissions. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019) include methods and default emission factors to estimate these emissions. In IPCC 2019, post-meter fugitives includes leak emissions from appliances in commercial and residential sectors (leakage from house piping and appliances, including home heating, water heating, stoves, and barbecues), leakage at industrial plants and power stations (leakage beyond gas meters including internal piping), and leakage from natural gas-fueled vehicles (vehicles with fuels produced from natural gas e.g., LNG, CNG, RNG).

For consistency with IPCC 2019, and to improve completeness of the Inventory estimates, EPA is considering updating next year's Inventory to include this emission source. EPA will seek stakeholder feedback on emission factors and activity data for this source.

Anomalous Emissions Events (Well Blowouts)

In recent years, a number of studies have assessed and, in some cases, quantified total emissions for gas well blowout events.[95,96] EPA is considering updating next year's inventory to include these events. EPA will seek stakeholder feedback on estimates for this source.

Transmission and Storage

Storage Wells

As part of the stakeholder process for the current (1990 to 2019) Inventory, EPA developed draft CH_4 emission estimates for underground storage well leak emissions in the transmission and storage segment. EPA's considerations for this source are documented in the EPA memorandum *Inventory of U. S. Greenhouse Gas Emissions and Sinks 1990-2019: Updates Under Consideration to Natural Gas Underground Storage Well Emissions* (*Underground Storage Wells* memo).[97] EPA presented multiple options to calculate storage well emissions in the *Underground Storage Wells* memo, and in the public review draft of the Inventory, presented estimated emissions using a 'per station' EF along with underground storage station counts. EPA received comment suggesting a recent PHMSA data set for national storage well counts.[98] EPA is considering the use of the national storage well data set and the GSI emission factors in next year's Inventory.

Table 3-94: Draft Underground Storage Wells National Emissions (Metric Tons CH₄) and Well Counts — Not Included in Totals

Source	1990		2005		2015	2016	2017	2018	2019
Storage Wells CH₄ (EPA draft)ᵃ	7,838		7,431		7,566	7,508	7,489	7,431	7,566

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[95] See <https://www.pnas.org/content/116/52/26376>.

[96] See <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL090864>.

[97] Stakeholder materials, including draft memoranda for the current (i.e., 1990 to 2019) Inventory are available at <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

[98] See <https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids>.

Storage Wells CH$_4$ (PHMSA and GSI)[b]						7,523	7,483	7,426
Well Counts (PHMSA)						14,268	14,192	14,084
Current Estimate CH$_4$[c]	13,565	14,910		14,250	13,428	13,632	15,439	15,495
Current Estimate Well Counts	16,853	18,524		17,703	16,682	16,936	19,181	19,250

NA (Not Applicable)

[a] Estimate developed using a 'per station' weighted average EF (based on data from the GSI 2019 study, GHGRP wellhead component counts, and field type distributions from EIA) and the number of underground storage stations over the time series (already in the Inventory).

[b] Estimate developed using PHMSA storage well counts and GSI emission factors. EPA has not developed an approach for the full time series for the activity data or emission factors, and is showing preliminary estimates for 2017 through 2019 emissions because those are the years where PHMSA storage well counts are available.

[c] The Current Estimate shows the routine storage well leak emissions only, to allow for a direct comparison, and does not include the Aliso Canyon leak emissions that occurred in 2015 and 2016 and that are included in the Inventory under the storage wells line item.

Transmission Station Counts

Stakeholder feedback suggested alternate approaches for calculating the annual number of transmission stations. EPA will consider the update for next year's Inventory.

Mud Degassing

As part of the stakeholder process for the current (1990 to 2019) Inventory, EPA developed new CH$_4$ emission estimates for onshore mud degassing in the exploration segment. To date, the Inventory has not included emissions from onshore exploration mud degassing. EPA's considerations for this source are documented in the EPA memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update Under Consideration for Mud Degassing Emissions (Mud Degassing* memo). EPA estimated preliminary emissions using CH$_4$ emission factors from EPA (EPA 1977) and well counts data from Enverus DrillingInfo data. In estimating national preliminary CH$_4$ estimates for mud degassing, EPA incorporated an estimate of 26 days as an average drilling duration and 61.2 percent (by weight) as the default CH$_4$ content of natural gas. EPA developed preliminary national estimates for 2 different scenarios: 1) EPA assumed 80 percent of drilling operations were performed using water-based muds and the remaining 20 percent used oil-based muds; and 2) EPA assumed 100 percent of drilling operations were performed using water-based muds. Methane emissions from mud degassing averaged 73 kt over the time series for scenario 1 and 86 kt for scenario 2 (100 percent water-based muds), or around 2 MMT CO$_2$ Eq. This update would increase emissions from the exploration segment but would have a small impact on overall CH$_4$ emissions from natural gas systems.

EPA notes that estimates for mud degassing using similar assumptions are included in several other bottom-up inventories for greenhouse gases and other gases, including New York state, and the NEI.

EPA received feedback on this update through its September 2020 memo and through the public review draft of the Inventory. A stakeholder indicated the 12 inch diameter borehole and 25 percent formation porosity assumptions used in developing the CH$_4$ emission factor for water-based muds are outdated and recommended that an 8 inch borehole diameter and 10 percent porosity should be considered in developing the CH$_4$ EF. A stakeholder commented that current onshore practices are to drill with balanced or slightly over-balanced mud systems that keep gas from being entrained in the drilling mud and that mud degassing systems are rarely needed or used. A stakeholder also indicated that mainly oil-based muds are used for horizontal/lateral drilling and water-based muds are more frequently used for vertical drilling.

Additionally, EPA also received comments on the average drilling duration used in developing the draft estimates for onshore mud degassing. A stakeholder comment stated that EPA should only consider the duration the drill

spends in the producing formation. Another comment indicated that EPA's average drilling duration assumption of 26 days per well is high and presented 2 examples–a Marcellus well takes 10 days to drill with 2-3 days in the producing formation; and the drilling duration in the Fayetteville shale dropped from 20 days in 2007 to 11 days in 2009. EPA's average drilling duration assumption of 26 days per well is comparable to average drilling duration developed from other inventories (New York – 24 days/well and CenSARA – 22 days/well). Refer to the *Mud Degassing* memo for further details.

EPA continues to seek feedback on average total drilling days and drilling days in the producing formation, CH_4 content of the gas, and the effect of balanced and over-balanced mud degassing systems. EPA will further assess the average drilling duration using updated Enverus data. Additionally, EPA is considering developing CO_2 estimates for onshore production mud degassing using the CH_4 estimates and a ratio of CO_2-to-CH_4.

Table 3-95: Draft Mud Degassing National CH₄ Emissions – Not Included in Totals (Metric Tons CH₄)

Source	1990		2005		2015	2016	2017	2018	2019
Scenario 1 (80/20)	95,133		146,766		18,211	11,736	19,301	19,301	19,301
Scenario 2 (100)	111,922		172,666		21,425	13,808	22,707	22,707	22,707
Previous Estimate	*NA*		*NA*		*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)
Scenario 1 (80/20) – 80% water-based mud usage and 20% oil-based mud usage
Scenario 2 (100) – 100% water-based mud usage

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the EPA Methane Challenge Program on an ongoing basis, which may be used to validate or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory. EPA will also continue to assess studies that include and compare both top-down and bottom-up emission estimates, which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank and flaring malfunction and control efficiency data.
- Improved equipment leak data
- Activity data and emissions data for production facilities that do not report to GHGRP.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

3.8 Abandoned Oil and Gas Wells (CRF Source Categories 1B2a and 1B2b)

The term "abandoned wells" encompasses various types of wells, including orphaned wells and other non-producing wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.

- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

The U.S. population of abandoned wells (including orphaned wells and other non-producing wells) is around 3.4 million (with around 2.7 million abandoned oil wells and 0.6 million abandoned gas wells). The methods to calculate emissions from abandoned wells involve calculating the total populations of plugged and unplugged abandoned oil and gas wells in the U.S. An estimate of the number of orphaned wells within this population is not developed as part of the methodology. Wells that are plugged have much lower average emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 40 percent of the abandoned well population in the United States is plugged. This fraction has increased over the time series (from around 19 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 209 kt CH_4 and 4 kt CO_2 in 2019. Emissions of both gases decreased by 10 percent from 1990, while the total population of abandoned oil wells increased 28 percent.

Abandoned gas wells. Abandoned gas wells emitted 55 kt CH_4 and 2 kt CO_2 in 2019. Emissions of both gases increased by 38 percent from 1990, as the total population of abandoned gas wells increased 84 percent.

Table 3-96: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Oil Wells	5.8		6.0		5.9	5.9	5.7	5.8	5.2
Abandoned Gas Wells	1.0		1.2		1.5	1.5	1.5	1.5	1.4
Total	**6.8**		**7.2**		**7.4**	**7.4**	**7.2**	**7.3**	**6.6**

Note: Totals may not sum due to independent rounding.

Table 3-97: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Oil Wells	231		238		235	236	229	231	209
Abandoned Gas Wells	40		49		59	60	58	59	55
Total	**271**		**287**		**294**	**296**	**288**	**290**	**263**

Note: Totals may not sum due to independent rounding.

Table 3-98: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Oil Wells	+		+		+	+	+	+	+
Abandoned Gas Wells	+		+		+	+	+	+	+
Total	**+**		**+**		**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2.

Table 3-99: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Abandoned Oil Wells	5		5		5	5	5	5	4
Abandoned Gas Wells	2		2		3	3	3	3	2
Total	**6**		**7**		**7**	**7**	**7**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Methodology

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to all other abandoned wells.

EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4.

The total population of abandoned wells over the time series was estimated using historical data and Enverus data. The total abandoned well population was then split into plugged and unplugged wells by assuming that all abandoned wells were unplugged in 1950, using year-specific Enverus data to calculate the fraction of plugged abandoned wells (31 percent in 2016, 34 percent in 2017 and 2018, and 41 percent in 2019), and applying linear interpolation between the 1950 value and 2016 value to calculate the plugged fraction for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[99] Due to changes in the structure of the Enverus data, the fraction of abandoned wells that are plugged was calculated uniquely for 2019. See Planned Improvements section below for more information.

Abandoned Oil Wells

Table 3-100: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990		2005		2015	2016	2017	2018	2019
Plugged abandoned oil wells	394,907		624,930		789,418	809,774	890,458	905,866	1,109,167
Unplugged abandoned oil wells	1,720,692		1,809,892		1,813,090	1,819,396	1,765,889	1,777,547	1,604,291
Total Abandoned Oil Wells	2,115,599		2,434,821		2,602,508	2,629,170	2,656,346	2,683,413	2,713,458
Abandoned oil wells in Appalachia	26%		24%		23%	23%	23%	23%	23%
Abandoned oil wells outside of Appalachia	74%		76%		77%	77%	77%	77%	77%
CH_4 from plugged abandoned oil wells (MT)	0		0		1	1	1	1	1

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[99] See <https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems>.

Source	1990		2005		2015	2016	2017	2018	2019
CH_4 from unplugged abandoned oil wells (MT)	231		238		235	236	229	230	208
Total CH_4 from Abandoned oil wells (MT)	**231**		**238**		**235**	**236**	**229**	**231**	**209**
Total CO_2 from Abandoned oil wells (MT)	**5**		**5**		**5**	**5**	**5**	**5**	**4**

Abandoned Gas Wells

Table 3-101: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source	1990		2005		2015	2016	2017	2018	2019
Plugged abandoned gas wells	65,559		119,655		179,428	186,116	206,735	212,338	264,277
Unplugged abandoned gas wells	285,654		346,540		412,101	418,164	409,982	416,663	382,248
Total Abandoned Gas Wells	351,213		466,196		591,529	604,280	616,717	629,001	646,525
Abandoned gas wells in Appalachia	28%		29%		30%	30%	30%	30%	30%
Abandoned gas wells outside of Appalachia	72%		71%		70%	70%	70%	70%	70%
CH_4 from plugged abandoned gas wells (kt)	0		0		0	0	0	0	0
CH_4 from unplugged abandoned gas wells (kt)	39		49		59	59	58	59	54
Total CH_4 from abandoned gas wells (kt)	**40**		**49**		**59**	**60**	**58**	**59**	**55**
Total CO_2 from abandoned gas wells (kt)	**2**		**2**		**3**	**3**	**3**	**3**	**2**

Uncertainty and Time-Series Consistency

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the *2018 Abandoned Wells Memo* for details of the uncertainty analysis methods. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells in year 2019, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of ± 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-102 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2019, using the recommended IPCC

methodology. Abandoned oil well CH_4 emissions in 2019 were estimated to be between 0.9 and 16.5 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.2 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-102: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum and Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	5.2	0.9	16.5	-83%	+217%
Abandoned Gas Wells	CH_4	1.4	0.2	4.3	-83%	+217%
Abandoned Oil Wells	CO_2	0.004	0.001	0.013	-83%	+217%
Abandoned Gas Wells	CO_2	0.002	0.0004	0.008	-83%	+217%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for total abandoned oil and gas well CH_4 emissions in year 2019.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

To calculate a time series of emissions for abandoned wells, EPA developed annual activity data for 1990 through 2019 by summing an estimate of total abandoned wells not included in recent databases, to an annual estimate of abandoned wells in the Enverus data set. As discussed above, the abandoned well population was split into plugged and unplugged wells by assuming that all abandoned wells were unplugged in 1950, using year-specific Enverus data to calculate the fraction of abandoned wells plugged in 2016 through 2019, and applying linear interpolation between the 1950 value and 2016 value to calculate plugged fraction for intermediate years. The same emission factors were applied to the corresponding categories for each year of the time series.

QA/QC and Verification Discussion

The emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies to assess whether the assumptions in the Inventory are consistent with industry practices and whether new data is available that could be considered for updates to the estimates. As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder webinars on greenhouse gas data for oil and gas in September and November of 2020.

Recalculations Discussion

The counts of national abandoned wells were recalculated across the time series to use the latest Enverus data, which resulted in changes to the total abandoned well population and the allocation between petroleum and natural gas systems. The changes resulted from changes to the year-specific data for 1990 to 2019 available in the restructured Enverus data, which led EPA to recalculate the 1975 estimate of historical wells not included in the Enverus data set (which increased from 1,075,849 to 1,152,211 historical wells not completely included in Enverus).

Compared with the previous Inventory, counts of abandoned oil and gas wells are on average 1 percent and 12 percent, respectively, higher over 1990 to 2018. Total methane emissions from abandoned wells are around 3 percent higher across the time series than the previous Inventory and CO_2 emissions are around 4 percent higher.

Planned Improvements

EPA will continue to assess new data and stakeholder feedback on considerations (such as disaggregation of the well population into regions other than Appalachia and non-Appalachia, and emission factor data from regions not included in the measurement studies on which current emission factors are based) to improve the abandoned well count estimates and emission factors.

As noted above in the Methodology section, Enverus, a key data source for the calculation of the number of abandoned wells in the U.S., has restructured its information on the U.S. well population. EPA will seek stakeholder feedback on how to consider the restructured Enverus dataset for future inventories.

In addition to the wells identified as abandoned through analysis of the Enverus population and included in the Inventory estimates, for 2019, EPA identified approximately 900,000 wells in the Enverus dataset with only limited data available for use in determining whether the wells should be included in the abandoned well population. These wells may be included in some fraction of the estimate of historical wells estimated outside of the Enverus data set, but the extent is unknown at this time. To develop the national count of abandoned wells in the inventory for 2019, EPA did not include these approximately 900,000 wells along with the other abandoned wells from the Enverus data set, due to the limited data, and still relied on the historical estimate to account for old abandoned wells. Note, including these approximately 900,000 wells would have limited overall impact on the total count of abandoned wells (including them would simply reduce the historical estimate for the number of estimated abandoned wells missing from the Enverus data), but would impact the fraction of plugged and unplugged abandoned wells, as discussed next.

Using the restructured Enverus dataset, for the year 2019, the well status for approximately 400,000 wells in Texas changed from 'inactive' to 'P&A' (P&A = plugged and abandoned). Applying the same approach to calculating the fraction of plugged wells as in prior Inventories would have resulted in a large change in plugging status from year 2018 (34 percent plugged) to year 2019 (62 percent plugged). For this year's Inventory, due to lack of clarity on the 900,000 wells noted in the paragraph above and on the 400,000 wells with changed plugging status, EPA calculated that 41 percent of abandoned wells are plugged for year 2019 by incorporating an assumption that all historical wells (those outside of the abandoned wells counts developed with Enverus) were not plugged. In other years of the time series, EPA relies only on the plugging status data available in Enverus and applies the calculated fraction to all abandoned wells.

EPA will seek stakeholder feedback on other approaches to estimate the total national abandoned well counts and the plugged abandoned well population, including feedback on how the approximately 900,000 wells with limited data should be considered.

3.9 Energy Sources of Precursor Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, energy-related activities are also sources of precursor gases. The reporting requirements of the UNFCCC[100] request that information be provided on precursor greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-CH_4 volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse

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[100] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

gases. Total emissions of NOₓ, CO, and NMVOCs from energy-related activities from 1990 to 2019 are reported in Table 3-103. Sulfur dioxide emissions are presented in Section 2.3 of the Trends chapter and Annex 6.3.

Table 3-103: NOₓ, CO, and NMVOC Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2015	2016	2017	2018	2019
NOₓ	**21,106**	**16,602**	**9,429**	**8,268**	**7,928**	**7,471**	**7,080**
Mobile Fossil Fuel Combustion	10,862	10,295	5,634	4,739	4,563	4,123	3,862
Stationary Fossil Fuel Combustion	10,023	5,858	3,084	2,856	2,728	2,711	2,581
Oil and Gas Activities	139	321	622	594	565	565	565
Waste Combustion	82	128	88	80	71	71	71
International Bunker Fuels[a]	1,956	1,704	1,363	1,470	1,481	1,462	1,296
CO	**125,640**	**64,985**	**38,521**	**34,461**	**33,582**	**32,048**	**31,208**
Mobile Fossil Fuel Combustion	119,360	58,615	32,635	28,789	28,124	26,590	25,749
Stationary Fossil Fuel Combustion	5,000	4,648	3,688	3,690	3,692	3,692	3,692
Waste Combustion	978	1,403	1,576	1,375	1,175	1,175	1,175
Oil and Gas Activities	302	318	622	607	592	592	592
International Bunker Fuels[a]	103	133	144	150	156	160	157
NMVOCs	**12,620**	**7,191**	**6,738**	**5,941**	**5,626**	**5,410**	**5,304**
Mobile Fossil Fuel Combustion	10,932	5,724	3,458	2,873	2,758	2,543	2,437
Oil and Gas Activities	554	510	2,656	2,459	2,262	2,262	2,262
Stationary Fossil Fuel Combustion	912	716	493	489	496	496	496
Waste Combustion	222	241	132	121	109	109	109
International Bunker Fuels[a]	57	54	47	50	51	51	46

Note: Totals may not sum due to independent rounding.

[a] These values are presented for informational purposes only and are not included in totals.

Methodology

Emission estimates for 1990 through 2019 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2020), and disaggregated based on EPA (2003). Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual applications from various agencies.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data. A quantitative uncertainty analysis was not performed.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.10   International Bunker Fuels (CRF Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[101] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[102]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[103] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between three different modes of air traffic: civil aviation, military aviation, and general aviation. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil and military aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[104]

Emissions of CO_2 from aircraft are essentially a function of fuel consumption. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are reported as zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase.

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going

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[101] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[102] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[103] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

[104] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2019 from the combustion of international bunker fuels from both aviation and marine activities were 117.2 MMT CO_2 Eq., or 12.1 percent above emissions in 1990 (see Table 3-104 and Table 3-105). Emissions from international flights and international shipping voyages departing from the United States have increased by 112.2 percent and decreased by 46.0 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

Table 3-104: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990		2005		2015	2016	2017	2018	2019
CO_2	**103.5**		**113.2**		**110.9**	**116.6**	**120.1**	**122.1**	**116.1**
Aviation	38.0		60.1		71.9	74.1	77.7	80.8	80.7
Commercial	*30.0*		*55.6*		*68.6*	*70.8*	*74.5*	*77.7*	*77.6*
Military	*8.1*		*4.5*		*3.3*	*3.3*	*3.2*	*3.1*	*3.1*
Marine	65.4		53.1		39.0	42.6	42.4	41.3	35.4
CH_4	**0.2**		**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation[a]	0.0		0.0		0.0	0.0	0.0	0.0	0.0
Marine	0.2		0.1		0.1	0.1	0.1	0.1	0.1
N_2O	**0.9**		**1.0**		**1.0**	**1.0**	**1.1**	**1.1**	**1.0**
Aviation	0.4		0.6		0.7	0.7	0.7	0.8	0.8
Marine	0.5		0.4		0.3	0.3	0.3	0.3	0.3
Total	**104.5**		**114.3**		**112.0**	**117.7**	**121.3**	**123.3**	**117.2**

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

[a] CH_4 emissions from aviation are estimated to be zero.

Table 3-105: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990		2005		2015	2016	2017	2018	2019
CO_2	**103,463**		**113,232**		**110,908**	**116,611**	**120,121**	**122,112**	**116,064**
Aviation	38,034		60,125		71,942	74,059	77,696	80,788	80,714
Marine	65,429		53,107		38,967	42,552	42,425	41,324	35,350
CH_4	**7**		**5**		**4**	**4**	**4**	**4**	**4**
Aviation[a]	0		0		0	0	0	0	0
Marine	7		5		4	4	4	4	4
N_2O	**3**		**3**		**3**	**3**	**4**	**4**	**3**
Aviation	1		2		2	2	3	3	3
Marine	2		1		1	1	1	1	1

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

[a] CH_4 emissions from aviation are estimated to be zero.

Methodology

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3 – CO_2 from Fossil Fuel Combustion. Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil are the same as used for CO_2 from Fossil Fuel Combustion and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this Inventory. Density conversions were taken from Chevron (2000), ASTM (1989), and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2020) and USAF (1998), and heat content for jet fuel was taken from EIA (2020).

A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which is also referenced in the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.315 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990 and 2000 through 2019 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2019 were obtained directly from FAA's AEDT model (FAA 2021). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990 and 2000 through 2019 was not possible for 1991 through 1999 because the radar dataset was not available for years prior to 2000. FAA developed Official Airline Guide (OAG) schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000, and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data. See Annex 3.3 for more information on the methodology for estimating emissions from commercial aircraft jet fuel consumption.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2020). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-106. See Annex 3.8 for additional discussion of military data.

Table 3-106: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990		2005		2015	2016	2017	2018	2019
U.S. and Foreign Carriers	3,222		5,983		7,383	7,610	8,011	8,352	8,344
U.S. Military	862		462		341	333	326	315	318
Total	**4,084**		**6,445**		**7,725**	**7,943**	**8,338**	**8,667**	**8,662**

Note: Totals may not sum due to independent rounding.

In order to quantify the civilian international component of marine bunker fuels, activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were collected for individual shipping agents on a monthly basis by the U.S. Customs and Border Protection. This information was then reported in unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2020) for 1990 through 2001, 2007 through 2019, and the Department of Homeland Security's *Bunker Report* for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2020). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-107.

Table 3-107: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990		2005		2015	2016	2017	2018	2019
Residual Fuel Oil	4,781		3,881		2,718	3,011	2,975	2,790	2,246
Distillate Diesel Fuel & Other	617		444		492	534	568	684	702
U.S. Military Naval Fuels	522		471		326	314	307	285	281
Total	**5,920**		**4,796**		**3,536**	**3,858**	**3,850**	**3,759**	**3,229**

Note: Totals may not sum due to independent rounding.

Uncertainty and Time-Series Consistency

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[105] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the DoD Components (e.g., Army, Department of Navy and Air Force) from the Defense Logistics Agency Energy. These data may not include fuel used in aircraft and ships as a result of a Service procuring fuel from, selling fuel to, trading fuel with, or giving fuel to other ships, aircraft, governments, or other entities.

Additionally, there are uncertainties in historical aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be

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[105] See uncertainty discussions under section 3.1 Carbon Dioxide Emissions from Fossil Fuel Combustion.

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estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2019, including estimates for the quantity of jet fuel allocated to ground transportation. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, DoD data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through revalidation of assumptions based on data regarding current equipment and operational tempo, however, it is doubtful data with more fidelity exist at this time.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[106]

There is also concern regarding the reliability of the existing DOC (1991 through 2019) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

In order to ensure the quality of the emission estimates from international bunker fuels, General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O emissions from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

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[106] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

Recalculations Discussion

EPA revised distillate fuel oil carbon contents, which affect marine distillate fuel oil consumption (EPA 2020). Revisions resulted in an average annual increase of less than 0.05 MMT CO_2 Eq. in emissions from marine residual and distillate fuel oil.

Planned Improvements

A longer-term effort is underway to consider the feasibility of including data from a broader range of domestic and international sources for bunker fuels. Potential sources include the International Maritime Organization (IMO) and their ongoing greenhouse gas analysis work, data from the U.S. Coast Guard on vehicle operation currently used in criteria pollutant modeling, and data from the International Energy Agency.

3.11 Wood Biomass and Biofuels Consumption (CRF Source Category 1A)

The combustion of biomass fuels—such as wood, charcoal, and wood waste and biomass-based fuels such as ethanol, biogas, and biodiesel—generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic C reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from wood biomass and biofuel consumption are not included specifically in summing energy sector totals. However, they are presented here for informational purposes and to provide detail on wood biomass and biofuels consumption.

In 2019, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 216.5 MMT CO_2 Eq. (216,533 kt) (see Table 3-108 and Table 3-109). As the largest consumer of woody biomass, the industrial sector was responsible for 61.3 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 25.2 percent of the total, while the electric power and commercial sectors accounted for the remainder.

Table 3-108: CO₂ Emissions from Wood Consumption by End-Use Sector (MMT CO₂ Eq.)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Industrial	135.3		136.3		138.5	138.3	135.4	135.0	132.6
Residential	59.8		44.3		52.9	45.6	43.8	53.3	54.5
Commercial	6.8		7.2		8.2	8.6	8.6	8.7	8.7
Electric Power	13.3		19.1		25.1	23.1	23.6	22.8	20.7
Total	**215.2**		**206.9**		**224.7**	**215.7**	**211.5**	**219.8**	**216.5**

Table 3-109: CO₂ Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Industrial	135,348		136,269		138,537	138,339	135,386	134,983	132,635
Residential	59,808		44,340		52,872	45,598	43,844	53,346	54,528
Commercial	6,779		7,218		8,176	8,635	8,634	8,669	8,693

Electric Power	13,252		19,074		25,146	23,140	23,647	22,795	20,677
Total	**215,186**		**206,901**		**224,730**	**215,712**	**211,511**	**219,794**	**216,533**

Note: Totals may not sum due to independent rounding.

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2019, the United States transportation sector consumed an estimated 1,150.2 trillion Btu of ethanol (95 percent of total), and as a result, produced approximately 78.7 MMT CO_2 Eq. (78,739 kt) (see Table 3-110 and Table 3-111) of CO_2 emissions. Smaller quantities of ethanol were also used in the industrial and commercial sectors. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-110: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation[a]	4.1		21.6		74.2	76.9	77.7	78.6	78.7
Industrial	0.1		1.2		1.9	1.8	1.9	1.4	1.6
Commercial	0.1		0.2		2.8	2.6	2.5	1.9	2.2
Total	**4.2**		**22.9**		**78.9**	**81.2**	**82.1**	**81.9**	**82.6**

Note: Totals may not sum due to independent rounding.
[a] See Annex 3.2, Table A-81 for additional information on transportation consumption of these fuels.

Table 3-111: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation[a]	4,059		21,616		74,187	76,903	77,671	78,603	78,739
Industrial	105		1,176		1,931	1,789	1,868	1,404	1,627
Commercial	63		151		2,816	2,558	2,550	1,910	2,212
Total	**4,227**		**22,943**		**78,934**	**81,250**	**82,088**	**81,917**	**82,578**

Note: Totals may not sum due to independent rounding.
[a] See Annex 3.2, Table A-81 for additional information on transportation consumption of these fuels.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2020). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats, and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2020b).

In 2019, the United States consumed an estimated 231.3 trillion Btu of biodiesel, and as a result, produced approximately 17.1 MMT CO_2 Eq. (17,080 kt) (see Table 3-112 and Table 3-113) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2020b). There was no measured biodiesel consumption prior to 2001 EIA (2020).

Table 3-112: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation[a]	NO		0.9		14.1	19.6	18.7	17.9	17.1
Total	**NO**		**0.9**		**14.1**	**19.6**	**18.7**	**17.9**	**17.1**

Note: Totals may not sum due to independent rounding.
NO (Not Occurring)
[a] See Annex 3.2, Table A-81 for additional information on transportation consumption of these fuels.

Table 3-113: CO₂ Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation[a]	NO		856		14,077	19,648	18,705	17,936	17,080
Total	**NO**		**856**		**14,077**	**19,648**	**18,705**	**17,936**	**17,080**

Note: Totals may not sum due to independent rounding.

NO (Not Occurring)

[a] See Annex 3.2, Table A-81 for additional information on transportation consumption of these fuels.

Methodology

Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2020) (see Table 3-114), provided in energy units for the industrial, residential, commercial, and electric power sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO₂ emission estimates. The woody biomass is assumed to contain black liquor and other wood wastes, have a moisture content of 12 percent, and undergo complete combustion to be converted into CO₂.

The amount of ethanol allocated across the transportation, industrial, and commercial sectors was based on the sector allocations of ethanol-blended motor gasoline. The sector allocations of ethanol-blended motor gasoline were determined using a bottom-up analysis conducted by EPA, as described in the Methodology section of Fossil Fuel Combustion. Total U.S. ethanol consumption from EIA (2020) was allocated to individual sectors using the same sector allocations as ethanol-blended motor gasoline. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/Qbtu (EPA 2010) to adjusted ethanol consumption estimates (see Table 3-115). The emissions from biodiesel consumption were calculated by applying an emission factor of 20.1 MMT C/Qbtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2020) (see Table 3-116).[107]

Table 3-114: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Industrial	1,441.9		1,451.7		1,475.9	1,473.8	1,442.3	1,438.0	1,413.0
Residential	580.0		430.0		512.7	442.2	425.2	517.3	528.8
Commercial	65.7		70.0		79.3	83.7	83.7	84.1	84.3
Electric Power	128.5		185.0		243.9	224.4	229.3	221.1	200.5
Total	**2,216.2**		**2,136.7**		**2,311.8**	**2,224.1**	**2,180.6**	**2,260.5**	**2,226.6**

Note: Totals may not sum due to independent rounding.

Table 3-115: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation	59.3		315.8		1,083.7	1,123.4	1,134.6	1,148.2	1,150.2
Industrial	1.5		17.2		28.2	26.1	27.3	20.5	23.8
Commercial	0.9		2.2		41.1	37.4	37.2	27.9	32.3
Total	**61.7**		**335.1**		**1,153.1**	**1,186.9**	**1,199.1**	**1,196.6**	**1,206.3**

Note: Totals may not sum due to independent rounding.

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[107] CO₂ emissions from biodiesel do not include emissions associated with the C in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Table 3-116: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990		2005		2015	2016	2017	2018	2019
Transportation	NO		11.6		190.6	266.1	253.3	242.9	231.3
Total	**NO**		**11.6**		**190.6**	**266.1**	**253.3**	**242.9**	**231.3**

Note: Totals may not sum due to independent rounding.

NO (Not Occurring)

Uncertainty and Time-Series Consistency

It is assumed that the combustion efficiency for woody biomass is 100 percent, which is believed to be an overestimate of the efficiency of wood combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

EIA (2020) revised approximate heat rates for electricity and the heat content of electricity for noncombustible renewable energy, which impacted wood energy consumption by the industrial sector from 2016 through 2018. Revisions to biomass consumption resulted in an average annual decrease of 0.7 MMT CO_2 Eq. (0.3 percent).

Planned Improvements

Future research will investigate the availability of data on woody biomass heat contents and carbon emission factors the see if there are newer, improved data sources available for these factors.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States, and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[108]

In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's

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[108] See <https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>.

GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[109]

Currently emission estimates from biomass and biomass-based fuels included in this Inventory are limited to woody biomass, ethanol, and biodiesel. Additional forms of biomass-based fuel consumption include biogas, the biogenic components of MSW, and other renewable diesel fuels. EPA will examine EIA data on biogas and other renewable diesel fuels to see if it can be included in future inventories. EIA (2020) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas. Distillate fuel statistics are adjusted in this Inventory to remove other renewable diesel fuels as well as biodiesel. Sources of estimates for the biogenic fraction of MSW will be examined, including the GHGRP, EIA data, and EPA MSW characterization data.

Carbon dioxide emissions from biomass used in the electric power sector are calculated using woody biomass consumption data from EIA's *Monthly Energy Review* (EIA 2020a), whereas non-CO_2 biomass emissions from the electric power sector are estimated by applying technology and fuel use data from EPA's Clean Air Market Acid Rain Program dataset (EPA 2021) to fuel consumption data from EIA (2020a). There were significant discrepancies identified between the EIA woody biomass consumption data and the consumption data estimated using EPA's Acid Rain Program dataset (see the Methodology section for CH_4 and N_2O from Stationary Combustion). EPA will continue to investigate this discrepancy in order to apply a consistent approach to both CO_2 and non-CO_2 emission calculations for woody biomass consumption in the electric power sector.

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[109] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4. Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, lime production, ammonia production, nitric acid production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), urea consumption for non-agricultural purposes, adipic acid production, HCFC-22 production, aluminum production, soda ash production and use, ferroalloy production, titanium dioxide production, caprolactam production, glass production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs is growing rapidly since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by semiconductor manufacturing and anesthetic and aerosol applications.

In 2019, IPPU generated emissions of 373.7 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 5.7 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 166.6 MMT CO_2

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[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories to the extent of which industries are occurring.

Eq. (166,589 kt CO_2) in 2019, or 3.2 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.4 MMT CO_2 Eq. (15 kt CH_4) in 2019, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 21.1 MMT CO_2 Eq. (71 kt N_2O) in 2019, or 4.6 percent of total U.S. N_2O emissions. In 2019 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 185.7 MMT CO_2 Eq. Total emissions from IPPU in 2019 were 8.1 percent more than 1990 emissions. Indirect greenhouse gas emissions also result from IPPU and are presented in Table 4-112 in kilotons (kt).

Figure 4-1: 2019 Industrial Processes and Product Use Chapter Greenhouse Gas Sources
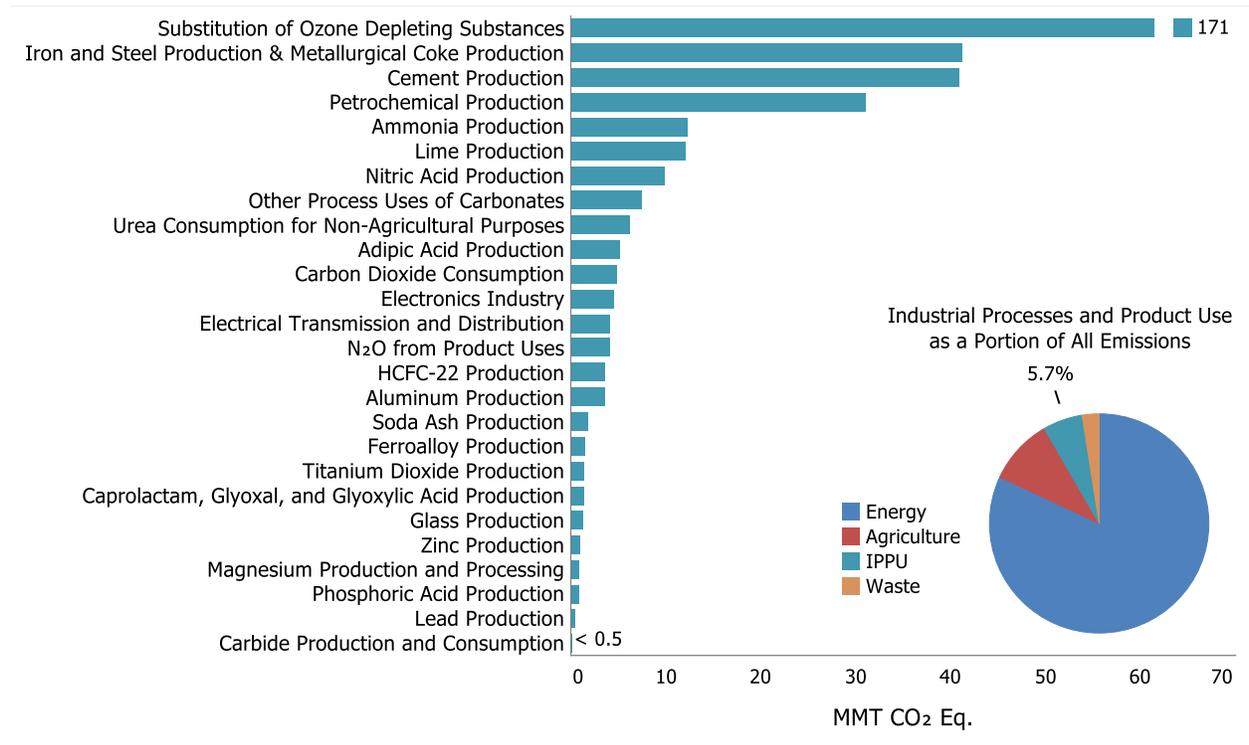
Figure 4-2: Trends in Industrial Processes and Product Use Chapter Greenhouse Gas Sources
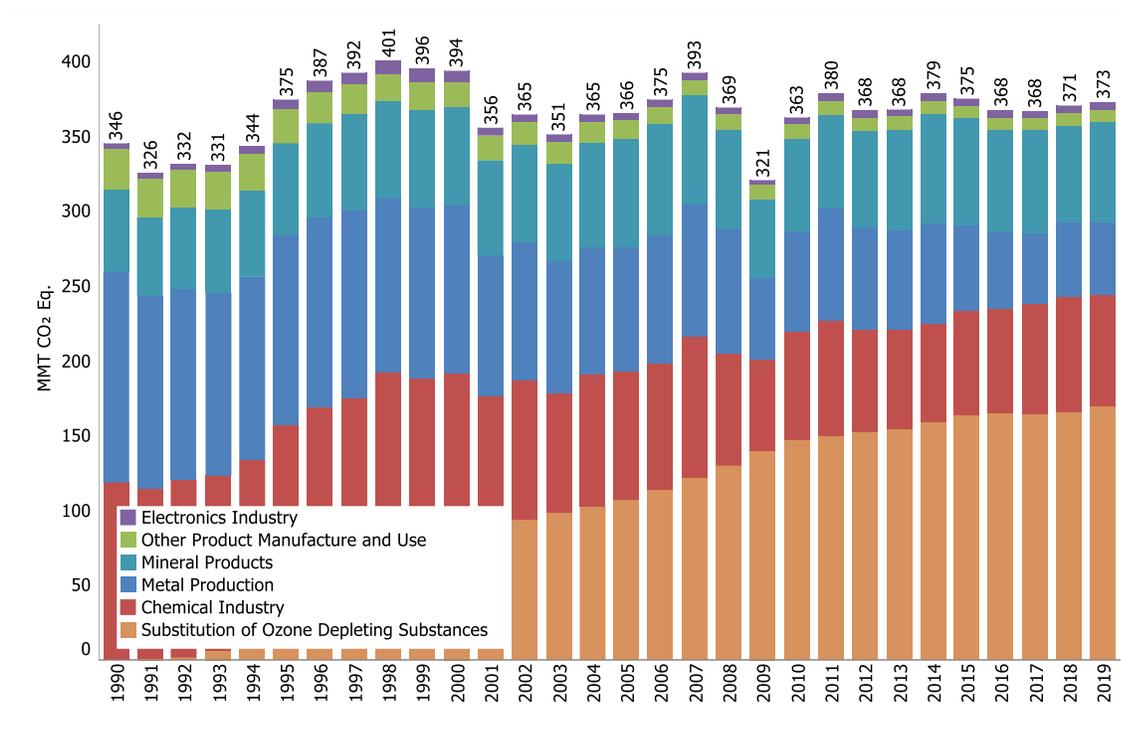
The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from many chemical production sources have either decreased or not changed significantly since 1990, with the exception of petrochemical production, Carbon Dioxide Consumption, and Urea Consumption for Non-Agricultural Purposes which has steadily increased. Emissions from mineral sources have either increased (e.g., Cement Production) or not changed significantly (e.g., Glass and Lime Production) since 1990 but largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (45.6 percent in 2019), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of adipic and nitric acid have decreased, while N_2O emissions from product uses have remained nearly constant over time. Some emission sources exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter. Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using *IPCC Fourth Assessment Report* (AR4) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted native gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Format (CRF) tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to

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[2] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

ensure that the trend is accurate. This year's estimates of HFC emissions from use of Ozone Depleting Substances Substitutes reflect updates to market size, substitute transitions, and charge size assumptions for Metered Dose Inhalers (MDI) aerosols to align with stakeholder input and market research. Market transitions for the ice maker end-use were updated based on manufacturer information on refrigerant use. In addition, several updates to the foam sector were implemented. The commercial refrigeration foam end-use was replaced with ten discrete commercial refrigeration application end-uses, in order to better define a market that was not adequately encompassed by the current commercial refrigeration foam end-use. Within the domestic refrigerator foam end-use, manufacturing emissions were adjusted to only include equipment manufactured within the United States, including those that are produced for export, and excluding those that are imported with foam. Market size, manufacturing loss rate, disposal lost rate, and post-life emission rate assumptions were also updated for PU and PIR boardstock foams based on market research. Carbon content factors were also updated for the Iron and Steel emissions calculations. Finally, the methods to estimate the CO_2 emission factors to recalculate emissions for earlier parts of the time series (i.e., 1990 to 2009) for petrochemical subcategories ethylene, ethylene dichloride and vinyl chloride monomer, and carbon black were updated to reflect GHGRP data updates. Together, these updates decreased greenhouse gas emissions an average of 0.081 MMT CO_2 Eq. (0.04 percent) across the time series.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO₂ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO₂	**212.3**	**194.1**	**173.5**	**165.3**	**163.9**	**164.3**	**166.6**
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	47.9	43.6	40.6	42.6	41.3
Iron and Steel Production	*99.1*	*66.2*	*43.5*	*41.0*	*38.6*	*41.3*	*39.9*
Metallurgical Coke Production	*5.6*	*3.9*	*4.4*	*2.6*	*2.0*	*1.3*	*1.4*
Cement Production	33.5	46.2	39.9	39.4	40.3	39.0	40.9
Petrochemical Production	21.6	27.4	28.1	28.3	28.9	29.3	30.8
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Lime Production	11.7	14.6	13.3	12.6	12.9	13.1	12.1
Other Process Uses of Carbonates	6.3	7.6	12.2	11.0	9.9	7.5	7.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.6	5.1	5.0	5.9	6.2
Carbon Dioxide Consumption	1.5	1.4	4.9	4.6	4.6	4.1	4.9
Aluminum Production	6.8	4.1	2.8	1.3	1.2	1.5	1.9
Soda Ash Production	1.4	1.7	1.7	1.7	1.8	1.7	1.8
Ferroalloy Production	2.2	1.4	2.0	1.8	2.0	2.1	1.6
Titanium Dioxide Production	1.2	1.8	1.6	1.7	1.7	1.5	1.5
Glass Production	1.5	1.9	1.3	1.2	1.3	1.3	1.3
Zinc Production	0.6	1.0	0.9	0.8	0.9	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	1.0	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
CH₄	**0.3**	**0.1**	**0.2**	**0.3**	**0.3**	**0.3**	**0.4**
Petrochemical Production	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Ferroalloy Production	+	+	+	+	+	+	+
Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
N₂O	**33.3**	**24.9**	**22.2**	**23.3**	**22.7**	**25.8**	**21.1**
Nitric Acid Production	12.1	11.3	11.6	10.1	9.3	9.6	10.0

Gas/Source						
Adipic Acid Production	15.2	7.1	4.3	7.0	7.4	10.3	5.3
N₂O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.9	1.7	1.5	1.4	1.4
Electronics Industry	+	0.1	0.2	0.2	0.3	0.3	0.2
HFCs	**46.5**	**127.5**	**168.3**	**168.1**	**170.3**	**169.8**	**174.6**
Substitution of Ozone Depleting Substances[a]	0.2	107.3	163.6	164.9	164.7	166.0	170.5
HCFC-22 Production	46.1	20.0	4.3	2.8	5.2	3.3	3.7
Electronics Industry	0.2	0.2	0.3	0.3	0.4	0.4	0.3
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**5.2**	**4.4**	**4.1**	**4.7**	**4.5**
Electronics Industry	2.8	3.3	3.1	2.9	2.9	3.0	2.7
Aluminum Production	21.5	3.4	2.1	1.4	1.1	1.6	1.8
Substitution of Ozone Depleting Substances	0.0	+	+	+	+	0.1	0.1
SF₆	**28.8**	**11.8**	**5.5**	**6.0**	**5.9**	**5.7**	**5.9**
Electrical Transmission and Distribution	23.2	8.4	3.8	4.1	4.2	3.9	4.2
Magnesium Production and Processing	5.2	2.7	1.0	1.1	1.0	1.0	0.9
Electronics Industry	0.5	0.7	0.7	0.8	0.7	0.8	0.8
NF₃	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Unspecified Mix of HFCs, PFCs, SF₆, and NF₃	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+
Total	**345.6**	**365.7**	**375.4**	**368.0**	**367.7**	**371.3**	**373.7**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO₂ Eq.

[a] Small amounts of PFC emissions also result from this source.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO₂	**212,320**	**194,068**	**173,480**	**165,260**	**163,877**	**164,348**	**166,589**
Iron and Steel Production & Metallurgical Coke Production	104,732	70,076	47,941	43,621	40,566	42,627	41,310
Iron and Steel Production	*99,124*	*66,155*	*43,525*	*40,979*	*38,587*	*41,345*	*39,944*
Metallurgical Coke Production	*5,608*	*3,921*	*4,417*	*2,643*	*1,978*	*1,282*	*1,366*
Cement Production	33,484	46,194	39,907	39,439	40,324	38,971	40,896
Petrochemical Production	21,611	27,383	28,062	28,310	28,910	29,314	30,792
Ammonia Production	13,047	9,177	10,616	10,245	11,112	12,163	12,272
Lime Production	11,700	14,552	13,342	12,630	12,882	13,106	12,112
Other Process Uses of Carbonates	6,297	7,644	12,182	10,972	9,933	7,469	7,457
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,578	5,132	5,028	5,857	6,222
Carbon Dioxide Consumption	1,472	1,375	4,940	4,640	4,580	4,130	4,870
Aluminum Production	6,831	4,142	2,767	1,334	1,205	1,451	1,880
Soda Ash Production	1,431	1,655	1,714	1,723	1,753	1,714	1,792
Ferroalloy Production	2,152	1,392	1,960	1,796	1,975	2,063	1,598
Titanium Dioxide Production	1,195	1,755	1,635	1,662	1,688	1,541	1,474
Glass Production	1,535	1,928	1,299	1,249	1,296	1,305	1,280

Zinc Production	632		1,030		886	838	900	999	1,026
Phosphoric Acid Production	1,529	1,342	999	998	1,028	940	891
Lead Production	516	553	473	500	513	513	540
Carbide Production and Consumption	370	213	176	170	181	184	175
Magnesium Production and Processing	1	3	3	3	3	1	1
CH₄	**12**	**4**	**9**	**11**	**11**	**13**	**15**
Petrochemical Production	9	3	7	10	10	12	13
Ferroalloy Production	1	+	1	1	1	1	+
Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
N₂O	**112**	**84**	**74**	**78**	**76**	**87**	**71**
Nitric Acid Production	41	38	39	34	31	32	34
Adipic Acid Production	51	24	14	23	25	35	18
N₂O from Product Uses	14	14	14	14	14	14	14
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	6	6	5	5	5
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances	0	+	+	+	+	+	+
SF₆	**1**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
NF₃	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+
Unspecified Mix of HFCs, PFCs, SF₆, and NF₃	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

M (Mixture of gases)

[a] Small amounts of PFC emissions also result from this source.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this Inventory report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as that emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., ceramics, non-metallurgical magnesium production, glyoxal and glyoxylic acid

production, CH_4 from direct reduced iron production), emissions are included elsewhere within the Inventory report, or data suggest that emissions are not significant (e.g., various fluorinated gas emissions from the electronics industry and other produce uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from District of Columbia and U.S. Territories to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., cement production, lime production, and electrical transmission and distribution). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this Inventory. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRF Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and its supplements and

refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

For IPPU sources, a detailed QA/QC plan was developed and implemented for specific categories. This plan is consistent with the U.S. Inventory QA/QC plan outlined in Annex 8 but tailored to include specific procedures recommended for these sources. The IPPU QA/QC Plan does not replace the Inventory QA/QC Plan, but rather provides more context for the IPPU sector. The IPPU QA/QC Plan provides the completed QA/QC forms for each inventory reports, as well as, for certain source categories (e.g., key categories), more detailed documentation of quality control checks and recalculations due to methodological changes.

Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends to identify significant changes; that, where possible, consistent and reputable data sources are used and specified across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets, units, and conversion factors are used where applicable. The IPPU QA/QC plan also checked for transcription errors in data inputs required for emission calculations, including activity data and emission factors; and confirmed that estimates were calculated and reported for all applicable and able portions of the source categories for all years.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

General QA/QC procedures (Tier 1) and calculation-related QC (category-specific, Tier 2) have been performed for all IPPU sources. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories (such as the comparison of reported consumption with modeled consumption using EPA's Greenhouse Gas Reporting Program (GHGRP) data within Substitution of Ozone Depleting Substances) or sources where significant methodological and data updates have taken place. The QA/QC implementation did not reveal any significant inaccuracies, and all errors identified were documented and corrected. Application of these procedures, specifically category-specific QC procedures and

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[3] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations and Planned Improvement sections.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (See Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors. Descriptions of uncertainties and assumptions for activity data and emission factors are included within the uncertainty discussion sections for each IPPU source category.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines (IPCC 2011). In line with the UNFCCC reporting guidelines, the Inventory is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and *IPCC Technical Bulletin on Use of Facility-Specific Data in National GHG Inventories.*[4]

For certain source categories in this Inventory (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical transmission and distribution, HCFC-22 production, and magnesium production and processing.). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level

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[4] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See <http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting>.

[6] Ammonia Production, Glass Production, Lead Production, and Other Fluorinated Gas Production.

4.1 Cement Production (CRF Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks, is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln lime exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$
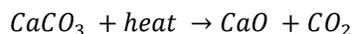
Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. Because these "sintering" reactions are highly exothermic, they produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements. Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2020). There are no additional emissions associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2 Lime Production (CRF Source Category 2A2).

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, California, Missouri, Florida, Alabama, Michigan, and Pennsylvania were the leading cement-producing states in 2019 and accounted for almost 60 percent of total U.S. production (USGS 2020). Clinker production in 2019 remained at relatively flat levels, compared to 2018 (EPA 2020; USGS 2020). In 2019, cement sales increased slightly, and imports of clinker for consumption increased by approximately 14 percent from 2018 (USGS 2020). In 2019, U.S. clinker production totaled 78,600 kilotons (EPA 2020). The resulting CO_2 emissions were estimated to be 40.9 MMT CO_2 Eq. (40,896 kt) (see Table 4-3).

Table 4-3: CO$_2$ Emissions from Cement Production (MMT CO$_2$ Eq. and kt)

Year	MMT CO$_2$ Eq.	kt
1990	33.5	33,484
2005	46.2	46,194
2015	39.9	39,907
2016	39.4	39,439
2017	40.3	40,324
2018	39.0	38,971
2019	40.9	40,896

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Since 1990, emissions have increased by 22 percent. Emissions from cement production were at their lowest levels in 2009 (2009 emissions are approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990) due to the economic recession and the associated decrease in demand for construction materials. Since 2010, emissions have increased by about 30 percent, due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology

Carbon dioxide emissions from cement production were estimated using the Tier 2 methodology from the *2006 IPCC Guidelines* as this is a key category. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime fraction for clinker of 65 percent and a constant reflecting the mass of CO$_2$ released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO$_2$ per ton of clinker produced, which was determined as follows:

$$\text{EF}_{\text{clinker}} = 0.650 \text{ CaO} \times [(44.01 \text{ g/mole CO}_2) \div (56.08 \text{ g/mole CaO})] = 0.510 \text{ tons CO}_2/\text{ton clinker}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO$_2$ emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO$_2$ emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO$_2$ emissions attributable to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used

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[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. In 2019, the percentage of facilities not using CEMS was 8 percent.

to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production (see Table 4-4) were obtained from USGS (Van Oss 2013a, Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current Inventory report utilize GHGRP data for the years 2014 through 2019 (EPA 2020). Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-4: Clinker Production (kt)

Year	Clinker
1990	64,355
2005	88,783
2015	76,700
2016	75,800
2017	77,500
2018	74,900
2019	78,600

Notes: Clinker production from 1990 through 2019 includes Puerto Rico (relevant U.S. Territories).

Uncertainty and Time-Series Consistency

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction

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[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary, but ranges typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss, 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss, 2005)…"

only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-5. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2019 CO_2 emissions from cement production were estimated to be between 38.5 and 43.4 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate of 40.9 MMT CO_2 Eq.

Table 4-5: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

| Source | Gas | 2019 Emission Estimate (MMT CO_2 Eq.) | Uncertainty Range Relative to Emission Estimate[a] | | | |
| | | | (MMT CO_2 Eq.) | | (%) | |
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	40.9	38.5	43.4	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the Inventory. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing Portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the Cement Production category are included in section 98.84, Monitoring and QA/QC Requirements.

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[10] See GHGRP Verification Fact Sheet <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

As mentioned above, EPA compares GHGRP clinker production data to the USGS clinker production data. For the year 2014 and 2018, USGS and GHGRP clinker production data showed a difference of approximately 2 percent and 3 percent, respectively. In 2015, 2016, 2017, and 2019, that difference was less than 1 percent between the two sets of activity data. This difference resulted in an increase of emissions compared to USGS data by less than 0.1 MMT CO_2 Eq. in 2015, 2016, 2017, and 2019. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

Recalculations were performed for year 2018 based on updated clinker production data from EPA's GHGRP. Compared to the previous Inventory, emissions for 2018 decreased by 3 percent (1,353 kt CO_2 Eq.).

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current Inventory.

Finally, in response to feedback from Portland Cement Association (PCA) during the Public Review comment period of a previous Inventory, EPA plans to work with PCA to discuss additional long-term improvements to review methods and data used to estimate CO_2 emissions from cement production to account for both organic material and magnesium carbonate in the raw material, and to discuss the carbonation that occurs across the duration of the cement product. Priority work includes identifying data and studies on the average MgO content of clinker produced in the United States, the average carbon content for organic materials in kiln feed in the United States, and CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to report to GHGRP. EPA met with PCA in the fall of 2020 to discuss PCA's latest research on carbonation.

4.2 Lime Production (CRF Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

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[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

$$CaCO_3 \rightarrow CaO + CO_2$$
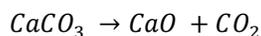
Some of the CO_2 generated during the production process, however, is recovered at some facilities for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] Emissions from fuels consumed for energy purposes during the production of lime are included in the Energy chapter.

For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ($[CaO \bullet MgO]$); and dolomitic hydrate ($[Ca(OH)_2 \bullet MgO]$ or $[Ca(OH)_2 \bullet Mg(OH)_2]$).

The current lime market is approximately distributed across five end-use categories, as follows: metallurgical uses, 34 percent; environmental uses, 30 percent; chemical and industrial uses, 21 percent; construction uses, 11 percent; and refractory dolomite, 1 percent (USGS 2020b). The major uses are in steel making, flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing. Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRF Source Category 2A4).

Emissions from lime production have increased and decreased over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 1996). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (USGS 1991 and 2020d).

The U.S. lime industry temporarily shut down individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2002).

Emissions from lime production increased and then peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2007, 2008, 2010). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2011 and 2012). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2018b, 2019, 2020b, 2020c).

Lime production in the United States—including Puerto Rico—was reported to be 16,897 kilotons in 2019 (USGS 2020a). Lime production in 2019 decreased by about 7 percent, compared to 2018 levels (USGS 2020a). Compared to 1990, lime production increased by about 7 percent. At year-end 2019, there were 74 operating primary lime plants in the United States, including Puerto Rico according to the USGS MCS (USGS 2020a).[13] Principal lime producing states are Missouri, Alabama, Ohio, Texas, and Kentucky (USGS 2020a).

U.S. lime production resulted in estimated net CO_2 emissions of 12.1 MMT CO_2 Eq. (12,112 kt) (see Table 4-6 and Table 4-7). Carbon dioxide emissions from lime production decreased by about 8 percent compared to 2018 levels.

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[12] PCC is obtained from the reaction of CO_2 with calcium hydroxide. It is used as a filler and/or coating in the paper, food, and plastic industries.

[13] In 2019, 71 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program due to closures.

Compared to 1990, CO_2 emissions have increased 3.5 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-6: CO_2 Emissions from Lime Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	11.7	11,700
2005	14.6	14,552
2015	13.3	13,342
2016	12.6	12,630
2017	12.9	12,882
2018	13.1	13,106
2019	12.1	12,112

Table 4-7: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt)

Year	Gross	Recovered[a]	Net Emissions
1990	11,959	259	11,700
2005	15,074	522	14,552
2015	13,764	422	13,342
2016	13,000	370	12,630
2017	13,283	401	12,882
2018	13,609	503	13,106
2019	12,676	564	12,112

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors using the Tier 2 approach from the *2006 IPCC Guidelines*. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.9500 \text{ CaO/lime}) = 0.7455 \text{ g } CO_2/\text{g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole CaO})] \times (0.9500 \text{ CaO/lime}) = 0.8675 \text{ g } CO_2/\text{g lime}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to [$Ca(OH)_2$ and [$Ca(OH)_2 \bullet Mg(OH)_2$]] (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the

application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRF Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2020) based on reported facility-level data for years 2010 through 2019. The amount of CO_2 captured/recovered for on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-6 and Table 4-7. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2019. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2019 (see Table 4-8) were obtained from U.S. Geological Survey (USGS) Minerals Yearbook (USGS 1992 through 2020d) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2018a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-9 (IPCC 2006). The CaO and CaO•MgO contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) were not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three-year distribution from 1997 to 1999.

Table 4-8: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
2005	14,100	2,990	2,220	474	200
2015	13,100	2,550	2,150	279	200
2016	12,100	2,420	2,350	280	200
2017	12,200	2,650	2,360	276	200
2018	12,400	2,810	2,430	265	200
2019	11,300	2,700	2,430	267	200

Table 4-9: Adjusted Lime Production (kt)

Year	High-Calcium	Dolomitic
1990	12,466	2,800
2005	15,721	3,522
2015	14,670	2,945
2016	13,816	2,816
2017	13,923	3,043
2018	14,174	3,196

| 2019 | 13,074 | 3,087 |

Note: Minus water content of hydrated lime.

Uncertainty and Time-Series Consistency

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2 reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net C fluxes from changes in biogenic C reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of

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[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) $[CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2]$, not calcium carbonate $[CaCO_3]$. Thus, the calcium hydroxide is heated in the kiln to simply expel the water $[Ca(OH)_2 + heat \rightarrow CaO + H_2O]$, and no CO_2 is released.

other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. Further research, including outreach and discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on IPCC guidelines. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions for 2019 were estimated to be between 11.9 and 12.4 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 12.1 MMT CO_2 Eq.

Table 4-10: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	12.1	11.9	12.4	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (Lime Manufacturing) of the GHGRP regulation (40 CFR Part 98).[16] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2020).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

Recalculations were performed for year 2018 based on updated CO_2 captured for on-site process use data obtained from EPA's GHGRP. Recalculations were performed for years 2015, 2016, 2017, and 2018 based on updated high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned

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[16] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[17] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

dolomite production data from revised USGS data (USGS 2020d). The updates resulted in less than a 1 percent decrease in CO_2 emissions for 2018 and a less than 1 percent increase in CO_2 emissions for 2015, 2016, and 2017, compared to the previous Inventory.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty and Time Series Consistency section, per comments from the NLA provided during a prior Public Review comment period for this (i.e., 1990 through 2018) and previous Inventories. EPA met with NLA in summer of 2020 for clarification on data needs and available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this Inventory, this planned improvement is in process and has not been incorporated into this current Inventory report.

4.3 Glass Production (CRF Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. Emissions from fuels consumed for energy purposes during the production of glass are included in the Energy sector.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers are used to make glass more chemically stable and to keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production

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[18] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (OIT 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,500 companies that manufacture glass in the United States, with the largest being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

In 2019, 2,220 kilotons of soda ash and 817 kilotons of limestone were consumed for glass production (USGS 2020; USGS 2020a). Dolomite consumption data for glass manufacturing was reported to be zero for 2019. Use of limestone and soda ash in glass production resulted in aggregate CO_2 emissions of 1.3 MMT CO_2 Eq. (1,280 kt) (see Table 4-11). Overall, emissions have decreased 17 percent from 1990 through 2019.

Emissions in 2019 decreased approximately 2 percent from 2018 levels while, in general, emissions from glass production have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone/dolomite and soda ash and resulting in lower emissions. Furthermore, the glass container sector is one of the leading soda ash consuming sectors in the United States. Some commercial food and beverage package manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b).

Table 4-11: CO_2 Emissions from Glass Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,535
2005	1.9	1,928
2015	1.3	1,299
2016	1.2	1,249
2017	1.3	1,296
2018	1.3	1,305
2019	1.3	1,280

Note: Totals may not sum due to independent rounding.

[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: <http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html>.

Methodology

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 3 method by multiplying the quantity of input carbonates (limestone, dolomite, and soda ash) by the carbonate-based emission factor (in metric tons CO_2/metric ton carbonate): limestone, 0.43971; dolomite, 0.47732; and soda ash, 0.41492.

In 1991, the U.S. Bureau of Mines, now known as the U.S. Geological Survey (USGS), began compiling production and end use information through surveys of crushed stone manufacturers. Each year, limestone and dolomite make up approximately 70% of the total crushed stone manufactured in the United States (USGS 1995 through 2016a). Crushed stone manufacturers provided different levels of detail in the survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production).

The "specified" production portion of the report provides limestone and dolomite consumption for glass manufacturing. Large quantities of limestone and dolomite consumption are reported under the categories "unspecified–reported" and "unspecified–estimated" as well, and a portion of this consumption is believed to be limestone or dolomite used for glass manufacturing. The quantities listed under both "unspecified" categories were allocated to glass manufacturing according to the percentage of "specified" limestone or dolomite consumed for glass manufacturing end-use for that year.[20]

During 1990 and 1992, the U.S. Bureau of Mines did not conduct a detailed survey of limestone and dolomite consumption by end-use. Therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite consumption by end use to the 1992 total limestone and dolomite consumption values.

For 1990 through 1993, consumption data of limestone and dolomite used for glass manufacturing were obtained from the U.S. Bureau of Mines (1991 and 1993a), For 1994 through 2018, consumption data of limestone and dolomite used for glass manufacturing were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2016a), and 2018 preliminary data from the USGS Crushed Stone Commodity Expert (Willett 2020a). The total limestone and dolomite used for glass manufacturing was determined in the same manner as described for 1991 above. For 2019, consumption data for limestone and dolomite used for glass manufacturing were not available at the time of publication, so 2018 values were used as proxy.

Each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; or (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years.

For 1990 through 2019, consumption data for soda ash used for glass manufacturing were obtained from the U.S. Bureau of Mines (1991 and 1993a), the *USGS Minerals Yearbook: Soda Ash Annual Report* (1995 through 2015b) (USGS 1995 through 2015b), and *USGS Mineral Industry Surveys for Soda Ash* in April 2020 (USGS 2020).

Based on the 2019 reported data, the estimated distribution of soda ash consumption for glass production compared to total domestic soda ash consumption is 47 percent (USGS 2020). Emissions from soda ash production are reported in 4.12 Soda Ash Production (CRF Source Category 2B7).

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[20] This approach was recommended by USGS.

Table 4-12: Limestone, Dolomite, and Soda Ash Consumption Used in Glass Production (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Limestone	430	920	699	472	720	818	817
Dolomite	59	541	0	0	0	0	0
Soda Ash	3,177	3,050	2,390	2,510	2,360	2,280	2,220
Total	**3,666**	**4,511**	**3,089**	**2,982**	**3,080**	**3,098**	**3,037**

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section arise in part due to variations in the chemical composition of limestone used in glass production. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals (potassium carbonate, strontium carbonate and barium carbonate, and dead burned dolomite). Similarly, the quality of the limestone (and mix of carbonates) used for glass manufacturing will depend on the type of glass being manufactured.

The estimates below also account for uncertainty associated with activity data. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the manufacturer of the input carbonates (limestone, dolomite and soda ash) and not the end user. For 2019, there has been no reported consumption of dolomite for glass manufacturing. These data have been reported to USGS by dolomite manufacturers and not end-users (i.e., glass manufacturers). There is a high uncertainty associated with this estimate, as dolomite is a major raw material consumed in glass production. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone and dolomite used in glass making is especially high. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. Further research is needed into alternate and more complete sources of data on carbonate-based raw material consumption by the glass industry.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-13. In 2019, glass production CO_2 emissions were estimated to be between 1.2 and 1.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 4 percent above the emission estimate of 1.3 MMT CO_2 Eq.

Table 4-13: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	1.3	1.2	1.3	-4%	+4%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current Inventory, updated USGS data on limestone and dolomite consumption became available for 2016 and 2018. The revised values resulted in increased emissions estimates for the years 2016 (increase of 0.6 percent) and 2018 (increase of 1.7 percent), compared to the previous Inventory.

Planned Improvements

As noted in the prior annual publications of this report, current publicly available activity data shows consumption of only limestone and soda ash for glass manufacturing. While limestone and soda ash are the predominant carbonates used in glass manufacturing, other carbonates are also consumed for glass manufacturing but in smaller quantities. EPA has initiated review of available activity data on carbonate consumption by type in the glass industry, reported annually since 2010 from EPA's Greenhouse Gas Reporting Program (GHGRP) as well as in USGS publications. This is a long-term planned improvement.

EPA has initiated review of GHGRP data to help understand the completeness of emission estimates and facilitate category-specific QC per Volume 1 of the *2006 IPCC Guidelines* for the Glass Production source category. GHGRP has an emission threshold for reporting from this industry, so the assessment will also consider the completeness of carbonate consumption data for glass production in the United States. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from GHGRP, EPA will rely on the latest guidance from the IPCC on the use of facility-level data in national inventories.[21] These planned improvements are ongoing, and EPA may also initiate research into other sources of activity data for carbonate consumption by the glass industry.

4.4 Other Process Uses of Carbonates (CRF Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[22] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control. This section addresses only limestone, dolomite, and soda ash use. For industrial applications, carbonates such as limestone and dolomite are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.
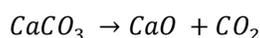
$$CaCO_3 \rightarrow CaO + CO_2$$

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[21] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

[22] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

$$MgCO_3 \rightarrow MgO + CO_2$$
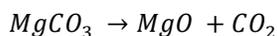
Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement. Emissions from limestone and dolomite used in other process sectors, such as cement, lime, glass production, and iron and steel, are excluded from the Other Process Uses of Carbonates category and reported under their respective source categories (e.g., Section 4.3, Glass Production). Emissions from soda ash production are reported under Section 4.12 Soda Ash Production (CRF Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.3 Glass Production (CRF Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Liming (CRF Source Category 3G). Emissions from fuels consumed for energy purposes during these processes are accounted for in the Energy chapter under Section 3.1 Fossil Fuel Combustion (CRF Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems are reported under Section 4.3 Lime Production (CRF Source Category 2A2).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2016, the leading limestone producing states were Texas, Florida, Missouri, Ohio, and Pennsylvania, which contributed 44 percent of the total U.S. output (USGS 2020a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2020a). Internationally, two types of soda ash are produced: natural and synthetic. In 2017, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2020b).

In 2019, 13,779 kilotons of limestone, 2,066 kt of dolomite, and 2,497 kt of soda ash were consumed for these emissive applications, excluding glass manufacturing (Willett 2020, USGS 2020b). Usage of limestone, dolomite and soda ash resulted in aggregate CO_2 emissions of 7.5 MMT CO_2 Eq. (7,457 kt) (see Table 4-14 and Table 4-15). Limestone and dolomite consumption data were not available for 2019, so 2018 data were used as a proxy. The 2018 and 2019 emissions decreased 25 percent compared to 2017, primarily as a result of decreased limestone consumption attributed to sulfur oxide removal usage for FGD systems. Overall emissions have increased 18 percent from 1990 through 2019.

Table 4-14: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	Flux Stone	FGD	Magnesium Production	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2.6	1.4	0.1	1.4	0.8	**6.3**
2005	2.6	3.0	0.0	1.3	0.7	**7.6**
2015	2.9	7.3	0.0	1.1	0.9	**12.2**
2016	2.6	6.2	0.0	1.1	1.1	**11.0**
2017	2.4	5.6	0.0	1.1	0.8	**9.9**
2018	2.8	2.2	0.0	1.1	1.4	**7.5**
2019	2.8	2.2	0.0	1.0	1.4	**7.5**

Note: Totals may not sum due to independent rounding.
[a] Soda ash consumption not associated with glass manufacturing.
[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 4-15: CO₂ Emissions from Other Process Uses of Carbonates (kt)

Year	Flux Stone	FGD	Magnesium Production	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2,592	1,432	64	1,390	819	**6,297**
2005	2,649	2,973	0	1,305	718	**7,644**
2015	2,901	7,335	0	1,075	871	**12,182**
2016	2,585	6,164	0	1,082	1,140	**10,972**
2017	2,441	5,598	0	1,058	835	**9,933**
2018	2,800	2,233	0	1,069	1,367	**7,469**
2019	2,821	2,233	0	1,036	1,367	**7,457**

Note: Totals may not sum due to independent rounding

[a] Soda ash consumption not associated with glass manufacturing.

[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Methodology

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[23] This methodology was used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Flux stone used during the production of iron and steel was deducted from the Other Process Uses of Carbonates source category estimate and attributed to the Iron and Steel Production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Historically, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO_2 emissions. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2020).

Consumption data for 1990 through 2018 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-16) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2017, 2020a, 2020c), preliminary data for 2018 from USGS Crushed Stone Commodity Expert (Willett 2020), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2020), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. For 2019, no data on limestone and dolomite consumption were available at the time of publication, so 2018 values were used as a proxy for these values. The production capacity data for 1990 through 2001 of dolomitic magnesium metal also came from the USGS (1995b through 2002) and the U.S. Bureau of Mines (1990 through 1993b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

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[23] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers, provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

There is a large quantity of crushed stone reported to the USGS under the category "unspecified uses." A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to all other reported end-uses according to each end-use's fraction of total consumption in that year.[24]

Table 4-16: Limestone and Dolomite Consumption (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Flux Stone	6,737	7,022	7,834	7,092	6,853	7,658	7,658
Limestone	*5,804*	*3,165*	*4,590*	*4118*	*4,920*	*5,603*	*5,603*
Dolomite	*933*	*3,857*	*3,244*	*2,973*	*1,933*	*2,055*	*2,055*
FGD	3,258	6,761	16,680	14,019	12,732	5,078	5,078
Other Miscellaneous Uses	1,835	1,632	1,982	2,592	1,900	3,108	3,108
Total	**11,830**	**15,415**	**26,496**	**23,703**	**21,484**	**15,845**	**15,845**

Once produced, most soda ash is consumed in chemical production, with minor amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2019 (see Table 4-17) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2017a, 2018, 2019, 2020). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-17: Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Soda Ash[a]	3,351	3,144	2,592	2,608	2,550	2,576	2,497
Total	**3,351**	**3,144**	**2,592**	**2,608**	**2,550**	**2,576**	**2,497**

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Uncertainty and Time-Series Consistency

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the

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[24] This approach was recommended by USGS, the data collection agency.

mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA's range of uncertainty was still reasonable (Willett 2017).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-18. Carbon dioxide emissions from other process uses of carbonates in 2019 were estimated to be between 6.6 and 8.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 7.5 MMT CO_2 Eq.

Table 4-18: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	7.5	6.6	8.6	-12%	+15%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the current Inventory, updated USGS data on limestone and dolomite consumption was available for 2016, 2017, and 2018, resulting in updated emissions estimates for those years. Compared to the previous Inventory, emissions for 2016 increased by 4 percent (467 kt CO_2 Eq.), decreased by less than 1 percent (2 kt CO_2 Eq.) for 2017, and decreased by 25 percent (2,485 kt CO_2 Eq.) for 2018.

Planned Improvements

In response to comments received during previous Inventory reports from the UNFCCC, EPA has inquired to the availability of ceramics and non-metallurgical magnesia data. The USGS notes that this data is not currently reported by survey respondents. EPA continues to conduct outreach with other entities, but at this time, the research has not yielded any alternative data on national levels of carbonates. This improvement remains ongoing, and EPA plans to continue to update this Planned Improvements section in future reports as more information becomes available.

EPA also plans to continue dialogue with USGS to assess uncertainty ranges for activity data used to estimate emissions from other process use of carbonates. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRF Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source; however, one synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2019, there were 16 companies operating 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in the states of Louisiana, Oklahoma, and Texas (USGS 2020).

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$
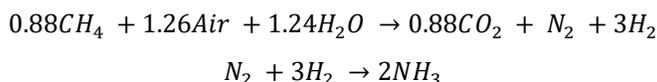
To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 Urea Fertilization (CRF Source Category 3H) of the Agriculture chapter. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.6 Urea Consumption for Non-Agricultural Purposes of this chapter.

Total emissions of CO_2 from ammonia production in 2019 were 12.3 MMT CO_2 Eq. (12,272 kt), and are summarized in Table 4-19 and Table 4-20. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by about 6 percent. Emissions in 2019 increased by about 1 percent from the 2018 levels. Emissions from ammonia production have increased steadily since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers and the need for new ammonia production capacity (USGS 2020).

Table 4-19: CO₂ Emissions from Ammonia Production (MMT CO₂ Eq.)

Source	1990	2005	2015	2016	2017	2018	2019
Ammonia Production	13.0	9.2	10.6	10.2	11.1	12.2	12.3
Total	**13.0**	**9.2**	**10.6**	**10.2**	**11.1**	**12.2**	**12.3**

Table 4-20: CO₂ Emissions from Ammonia Production (kt)

Source	1990	2005	2015	2016	2017	2018	2019
Ammonia Production	13,047	9,177	10,616	10,245	11,112	12,163	12,272
Total	**13,047**	**9,177**	**10,616**	**10,245**	**11,112**	**12,163**	**12,272**

Methodology

For this Inventory, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock are estimated using a country-specific approach modified from the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 methods. In the country-specific approach, emissions are not based on total fuel requirement per the *2006 IPCC*

Guidelines due to data disaggregation limitations of energy statistics provided by the Energy Information Administration (EIA). Data on total fuel use (including fuel used for ammonia feedstock and fuel used for energy) for ammonia production are not known in the U.S. EIA does not provide data broken out by industrial category, only at the broad industry sector level. To estimate emissions, a country-specific emission factor is developed and applied to national ammonia production to estimate ammonia-production emissions from feedstock fuel use. Emissions from fuel used for energy at ammonia plants are included in the overall EIA Industrial sector energy use and accounted for in the Energy Chapter.

The country-specific approach uses a CO_2 emission factor of 1.2 metric tons CO_2/metric ton NH_3 , which is published by the European Fertilizer Manufacturers Association (EFMA) and is based on natural gas-based ammonia production technologies that are similar to those employed in the United States (EFMA 2000a). The EFMA reported an emission factor range of 1.15 to 1.30 metric tons CO_2 per metric ton NH_3, with 1.2 metric tons CO_2 per metric ton NH_3 as a typical value (EFMA 2000a). Technologies (e.g., catalytic reforming process, etc.) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. This country-specific approach is compatible with the *2006 IPCC Guidelines* as it is based on the same scientific approach that the carbon in the fuel used to produce ammonia is released as CO_2. The CO_2 emission factor is applied to the percent of total annual domestic ammonia production from natural gas feedstock.

Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733 multiplied by total annual domestic urea production. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000b).

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at one plant located in Kansas. Annual ammonia and urea production are shown in Table 4-21.

The implied CO_2 emission factor for total ammonia production is a combination of the emission factors for ammonia production from natural gas and from petroleum coke. Changes in the relative production of ammonia from natural gas and petroleum coke will impact overall emissions and emissions per ton of total ammonia produced. For example, between 2000 and 2001 there were increases in the amount of ammonia produced from petroleum coke which caused increases in the implied emission factor across those years.

In previous Inventories, the CO_2 emission factor of 3.57 metric tons CO_2 per metric ton NH_3 for the petroleum coke feedstock process (Bark 2004) was applied to the percent of total annual domestic ammonia production from petroleum coke feedstock. Beginning with this Inventory, the CO_2 emission factor for petroleum coke feedstock was updated to 3.52 metric tons of CO_2 per metric ton of NH_3. The updated emission factor is based on an average of the ratio of ammonia production from petroleum coke for years 2010 through 2015 (ACC 2020) and the facility-specific CO_2 emissions from the one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock for years 2010 through 2015 (GHGRP 2020). Ammonia and urea are assumed to be manufactured in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process.

As a result of further examining the large increase in the amount of ammonia produced from petroleum coke between 2015 and 2016, another methodology change has been made for this Inventory. The amount of ammonia produced from petroleum coke changed significantly in 2016 because the parent company, CVR Energy, acquired a second plant that uses natural gas as a feedstock. Therefore, the amount of ammonia production reported by CVR Energy is no longer specific to the use of petroleum coke as a feedstock.

To correct this, beginning in 2016, the amount of CO_2 from the ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock (as reported under GHGRP 2020) is now being used,

along with the emission factor of 3.52 metric tons of CO_2 per metric ton of NH_3 to back-calculate the amount of ammonia produced through the use of petroleum coke as feedstock.

The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. See the Planned Improvements section on improvements of reporting fuel and feedstock CO_2 emissions utilizing EPA's GHGRP data to improve consistency with *2006 IPCC Guidelines*.

The total ammonia production data for 2011 through 2019 were obtained from American Chemistry Council (ACC 2020). For years before 2011, ammonia production data (see Table 4-21) were obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Urea-ammonia nitrate production from petroleum coke for years through 2011 was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012), and from *CVR Energy, Inc. Annual Report* (CVR 2012 through 2015) for 2012 through 2015. Urea production data for 1990 through 2008 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production values for the years 2011 through 2019 utilize GHGRP data (EPA 2018; EPA 2020).

Table 4-21: Ammonia Production, Recovered CO_2 Consumed for Urea Production, and Urea Production (kt)

Year	Ammonia Production	Total CO_2 Consumption for Urea Production	Urea Production
1990	15,425	5,463	7,450
2005	10,143	3,865	5,270
2015	11,765	4,312	5,880
2016	12,305	5,419	7,390
2017	14,070	6,622	9,030
2018	16,010	7,847	10,700
2019	16,410	8,360	11,400

Uncertainty and Time-Series Consistency

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to

determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22. Carbon dioxide emissions from ammonia production in 2019 were estimated to be between 10.9 and 13.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below and 11 percent above the emission estimate of 12.3 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.3	10.9	13.6	-11%	+11%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[25] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[26] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Recalculations Discussion

Recalculations of ammonia emissions were performed for the 1990 through 2018 portion of the time series as described below.

For years 2000 through 2018, the CO_2 emission factor for petroleum coke feedstock was updated from 3.57 metric tons of CO_2 per metric ton of NH_3 (Bark 2004) to 3.52 metric tons of CO_2 per metric ton of NH_3, as detailed in the Methodology section.

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[25] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[26] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

For years 2016 through 2018, the methodologies for determining the amount of ammonia produced using petroleum coke and for determining the amount of UAN produced using petroleum coke were changed, as detailed in the Methodology section.

For the year 2018, the amount of ammonia production increased by 11 percent due to a correction to the value used in the previous Inventory, based on the adjustments made in determining the amount of ammonia produced using petroleum coke as mentioned in the Methodology section.

These changes resulted in recalculations of the estimated CO_2 emissions estimates shown in Table 4-19 and Table 4-20 for the 1990 through 2018 portion of the time series. For years 2000 through 2015, the values reported decreased by less than 0.24 percent per year from the values reported in the previous Inventory report. For year 2016, the value decreased by 5 percent (593 kt CO_2); for year 2017, the value decreased by 16 percent (2,104 kt CO_2), and for year 2018, the value decreased by 10 percent (1,369 kt CO_2).

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for the Ammonia Production source category, in particular new data from updated reporting requirements finalized in October of 2014 (79 FR 63750) and December 2016 (81 FR 89188),[27] that include facility-level ammonia production data and feedstock consumption. The data were first reported by facilities in 2018 and available post-verification to assess in 2019 for use in future Inventories, if the data meet GHGRP CBI aggregation criteria. The data are still being evaluated and will be incorporated in future Inventory reports, if possible. Particular attention will be made to ensure time-series consistency of the emission estimates presented in future Inventory reports, along with application of appropriate category-specific QC procedures consistent with IPCC and UNFCCC guidelines. For example, data reported in 2018 will reflect activity in 2017 and may not be representative of activity in prior years of the time series. This assessment is required as the new facility-level reporting data from EPA's GHGRP associated with new requirements are only applicable starting with reporting of emissions in calendar year 2017, and thus are not available for all inventory years (i.e., 1990 through 2016) as required for this Inventory.

In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[28] Specifically, the planned improvements include assessing the anticipated new data to update the emission factors to include both fuel and feedstock CO_2 emissions to improve consistency with *2006 IPCC Guidelines,* in addition to reflecting CO_2 capture and storage practices (beyond use of CO_2 for urea production). Methodologies will also be updated if additional ammonia production plants are found to use hydrocarbons other than natural gas for ammonia production. Due to limited resources and ongoing data collection efforts, this planned improvement is still in development and is not incorporated into this Inventory. This is a long-term planned improvement.

4.6 Urea Consumption for Non-Agricultural Purposes

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2019, with two additional plants sitting idle for the entire year (USGS 2020).

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[27] See <https://www.epa.gov/ghgreporting/historical-rulemakings>.

[28] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 Urea Fertilization (CRF Source Category 3H) of the Agriculture chapter.

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2019 were estimated to be 6.2 MMT CO_2 Eq. (6,222 kt), and are summarized in Table 4-23 and Table 4-24. Net CO_2 emissions from urea consumption for non-agricultural purposes have increased by approximately 64 percent from 1990 to 2019. The increase in emissions since 2018 can be attributed to an increase in production and consumption.

Table 4-23: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990		2005		2015	2016	2017	2018	2019
Urea Consumption	3.8		3.7		4.6	5.1	5.0	5.9	6.2
Total	**3.8**		**3.7**		**4.6**	**5.1**	**5.0**	**5.9**	**6.2**

Table 4-24: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt)

Source	1990		2005		2015	2016	2017	2018	2019
Urea Consumption	3,784		3,653		4,578	5,132	5,028	5,857	6,222
Total	**3,784**		**3,653**		**4,578**	**5,132**	**5,028**	**5,857**	**6,222**

Methodology

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated by multiplying the amount of urea consumed in the United States for non-agricultural purposes by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use, consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* (IPCC 2006) which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea."

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-25. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of C in urea. This corresponds to a stoichiometric CO_2 to urea factor of 44/60, assuming complete conversion of C in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from

the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Starting with the Inventory report for the years 1990 through 2017, EPA began utilizing urea production data from EPA's GHGRP to estimate emissions. Urea production values in the current Inventory report utilize GHGRP data for the years 2011 through 2019 (EPA 2018, EPA 2020).

Urea import data for 2019 are not yet publicly available, so 2018 data have been used as a proxy. Urea import data for 2013 to 2018 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2019a). Urea import data for 2011 and 2012 were taken from *U.S. Fertilizer Import/Exports* from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for 1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-25).

Urea export data for 2019 are not yet publicly available, so 2018 data have been used as a proxy. Urea export data for 2013 to 2018 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2019a). Urea export data for 1990 through 2012 were taken from *U.S. Fertilizer Import/Exports* from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-25: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports	Urea Consumed for Non-Agricultural Purposes
1990	7,450	3,296	1,860	854	5,160
2005	5,270	4,779	5,026	536	4,981
2015	5,880	6,447	7,190	380	6,243
2016	7,390	6,651	6,580	321	6,998
2017	9,030	6,888	5,510	795	6,857
2018	10,700	7,080	5,110	743	7,987
2019	11,400	7,283	5,110	743	8,484

Uncertainty and Time-Series Consistency

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2019 were estimated to be between 5.4 and 7.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 14 percent above the emission estimate of 6.2 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]	
			(MMT CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	6.2	5.4	7.1	-13%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[29] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[30] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated urea production data from EPA's GHGRP for 2017 and 2018, updated urea imports from USGS for 2018, and updated urea exports from USGS for 2017 and 2018, recalculations were performed for these two years. Compared to the previous Inventory, CO_2 emissions from urea consumption for non-agricultural purposes increased by 33 percent (1,717 kt CO_2) for 2017 and 61 percent (3,039 kt CO_2) for 2018, due to large increases in urea production for both years.

4.7 Nitric Acid Production (CRF Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the high-temperature catalytic oxidation of ammonia (EPA 1998). There are two different nitric acid production methods: weak nitric acid and high-strength nitric acid. The first method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength acid (90

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[29] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[30] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

percent or greater nitric acid) can be produced from dehydrating, bleaching, condensing, and absorption of the weak nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2019, there were 31 active nitric acid production plants, including one high-strength nitric acid production plant in the United States (EPA 2010; EPA 2020).

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere. Emissions from fuels consumed for energy purposes during the production of nitric acid are included in the Energy chapter.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$
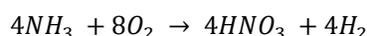
Currently, the nitric acid industry controls emissions of NO and NO_2 (i.e., NO_x). As such, the industry in the United States uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. NSCR units, however, are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCR systems were installed in nitric plants built between 1971 and 1977 and are used in approximately one-third of the weak acid production plants. U.S. facilities are using both tertiary (i.e., NSCR) and secondary controls (i.e., alternate catalysts).

Nitrous oxide emissions from this source were estimated to be 10.0 MMT CO_2 Eq. (34 kt of N_2O) in 2019 (see Table 4-27). Emissions from nitric acid production have decreased by 18 percent since 1990, while production has increased by 12 percent over the same time period. Emissions have decreased by 31 percent since 1997, the highest year of production in the time series.

Table 4-27: N₂O Emissions from Nitric Acid Production (MMT CO₂ Eq. and kt N₂O)

Year	MMT CO$_2$ Eq.	kt N$_2$O
1990	12.1	41
2005	11.3	38
2015	11.6	39
2016	10.1	34
2017	9.3	31
2018	9.6	32
2019	10.0	34

Methodology

Emissions of N_2O were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and a country-specific method utilizing EPA's GHGRP. The *2006 IPCC Guidelines* Tier 2 method was used to estimate emissions from nitric acid production for 1990 through 2009, and a country-specific approach similar to the IPCC Tier 3 method was used to estimate N_2O emissions for 2010 through 2019.

2010 through 2019

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2019 by aggregating reported facility-level data (EPA 2020).

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All greenhouse gas emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[31] All nitric acid facilities are required to calculate process emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment.[32]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded for consistency and are shown in Table 4-28.

1990 through 2009

Using GHGRP data for 2010,[33] country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year. At that time, EPA had initiated compilation of a nitric acid database to improve estimation of emissions from this industry and obtained updated information on application of controls via review of permits and outreach with facilities and trade associations. The research indicated recent installation of abatement technologies at additional facilities.

Based on the available data, it was assumed that emission factors for 2010 would be more representative of operating conditions in 1990 through 2009 than more recent years. Initial review of historical data indicates that percent production with and without abatement can change over time and from year to year due to changes in application of facility-level abatement technologies, maintenance of abatement technologies, and also due to plant closures and start-ups (EPA 2012, 2013; Desai 2012; CAR 2013). The installation dates of N_2O abatement technologies are not known at most facilities, but it is assumed that facilities reporting abatement technology use have had this technology installed and operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left\lfloor (\%P_{c,i} \times EF_c) + (\%P_{unc,i} \times EF_{unc}) \right\rfloor$$

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[31] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[32] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance tests and must follow associated QA/QC procedures consistent during these performance test consistent with category-specific QC of direct emission measurements.

[33] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology was aggregated from the GHGRP facility-level data for 2010 to 2017 (i.e., percent production with and without abatement).

where,

E_i = Annual N_2O Emissions for year i (kg/yr)
P_i = Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$ = Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$ = Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c = N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$ = Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc} = N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i = year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-28). Publicly available information on plant-level abatement technologies was used to estimate the shares of nitric acid production with and without abatement for 2008 and 2009 (EPA 2012, 2013; Desai 2012; CAR 2013). EPA has previously conducted a review of operating permits to obtain more current information due to the lack of publicly-available data on use of abatement technologies for 1990 through 2007, as stated previously; therefore, the share of national production with and without abatement for 2008 was assumed to be constant for 1990 through 2007.

Table 4-28: Nitric Acid Production (kt)

Year	kt
1990	7,200
2005	6,710
2015	7,210
2016	7,810
2017	7,780
2018	8,210
2019	8,080

Uncertainty and Time-Series Consistency

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low, high pressure, etc.), and abatement technology type, installation date of abatement technology, and accurate destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual

production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-29. Nitrous oxide emissions from nitric acid production were estimated to be between 9.5 and 10.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2019 emissions estimate of 10.0 MMT CO_2 Eq.

Table 4-29: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	10.0	9.5	10.5	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98).[34]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015).[35] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g. in the nitric production process and management of abatement equipment).

Recalculations Discussion

Recalculations of emissions from nitric acid production were performed for the 1990 through 2018 time series when the GHGRP data for 2018 were released in November 2020. Previously, the 2017 value was used as proxy for 2018. The change resulted in recalculations of the estimated CO_2 emissions estimates shown in Table 4-19 and Table 4-20. Compared to the previous Inventory, the emissions value for 2018 increased by 3 percent (0.3 MMT CO_2 Eq.), and the nitric acid production value for 2018 increased by 6 percent (430 kt).

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[34] See Subpart V monitoring and reporting regulation <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[35] See GHGRP Verification Factsheet <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Planned Improvements

Pending resources, EPA is considering both near-term and long-term improvement to estimates and associated characterization of uncertainty. In the short-term, with 8 years of EPA's GHGRP data, EPA anticipates completing updates of category-specific QC procedures to potentially also improve both qualitative and quantitative uncertainty estimates. In the next Inventory, EPA anticipates including information from GHGRP facilities on the installation date of any N_2O abatement equipment, per revisions finalized in December 2016 to EPA's GHGRP. This information will enable more accurate estimation of N_2O emissions from nitric acid production over the time series.

4.8 Adipic Acid Production (CRF Source Category 2B3)

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for in the Energy chapter. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3$$
$$\rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$
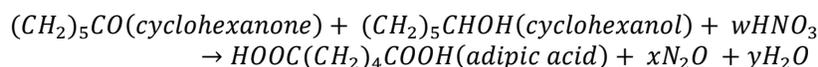
Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2018, catalytic reduction, non-selective catalytic reduction (NSCR), and thermal reduction abatement technologies were applied as N_2O abatement measures at adipic acid facilities (EPA 2019, 2020).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2019, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2019, 2020).

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

National adipic acid production has increased by approximately 7 percent over the period of 1990 through 2019, to approximately 810,000 metric tons (ACC 2020). Nitrous oxide emissions from adipic acid production were estimated to be 5.3 MMT CO_2 Eq. (18 kt N_2O) in 2019 (see Table 4-30). Over the period 1990 through 2019, emissions have been reduced by 65 percent due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. The total emissions from adipic acid production decreased by approximately 49 percent from GHGRP Reporting Year (RY) 2018 to RY2019 due to a significant change in emissions from one facility. The facility confirmed that there was a decrease in adipic acid production and an increase in the use of the N_2O abatement device in RY2019, resulting in a large decrease in greenhouse gas emissions (EPA 2019, 2020). As noted above, changes in control measures and abatement technologies at adipic

acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends in adipic acid production as it is not reported under EPA's GHGRP.

Table 4-30: N$_2$O Emissions from Adipic Acid Production (MMT CO$_2$ Eq. and kt N$_2$O)

Year	MMT CO$_2$ Eq.	kt N$_2$O
1990	15.2	51
2005	7.1	24
2015	4.3	14
2016	7.0	23
2017	7.4	25
2018	10.3	35
2019	5.3	18

Methodology

Emissions are estimated using both Tier 2 and Tier 3 methods consistent with the *2006 IPCC Guidelines.* Due to confidential business information (CBI), plant names are not provided in this section. Therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. Overall, as noted above, the two currently operating facilities use catalytic reduction, NSCR and thermal reduction abatement technologies.

2010 through 2019

All emission estimates for 2010 through 2019 were obtained through analysis of GHGRP data (EPA 2010 through 2020), which is consistent with the *2006 IPCC Guidelines* Tier 3 method. Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2019 (EPA 2010 through 2020) and aggregated to national N$_2$O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to calculate emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N$_2$O emissions using monitoring equipment.[36]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N$_2$O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

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[36] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

E_{aa}	=	N$_2$O emissions from adipic acid production, metric tons
Q_{aa}	=	Quantity of adipic acid produced, metric tons
EF_{aa}	=	Emission factor, metric ton N$_2$O/metric ton adipic acid produced
DF	=	N$_2$O destruction factor
UF	=	Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N$_2$O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N$_2$O per metric ton of product (IPCC 2006). The "N$_2$O destruction factor" in the equation represents the percentage of N$_2$O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2020; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-31) from 1990 through 2019 were obtained from the American Chemistry Council (ACC 2020).

Table 4-31: Adipic Acid Production (kt)

Year	kt
1990	755
2005	865
2015	1,055
2016	860
2017	830
2018	825
2019	810

Uncertainty and Time-Series Consistency

Uncertainty associated with N$_2$O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels.

The results of this Approach 2 quantitative uncertainty analysis are summarized in

Table 4-32. Nitrous oxide emissions from adipic acid production for 2019 were estimated to be between 5.0 and 5.5 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 5 percent below to 5 percent above the 2019 emission estimate of 5.3 MMT CO_2 Eq.

Table 4-32: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	5.3	5.0	5.5	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[37] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[38] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

EPA plans to review GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. See more detail on similar planned improvements within Section 4.7 on Nitric Acid Production presented above.

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[37] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[38] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRF Source Category 2B4)

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam begin with benzene, but toluene can also be used. The production of caprolactam can give rise to significant emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

Where caprolactam is produced from benzene, the main process, the benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation \ of \ NH_3 \ to \ NO/NO_2$$
$$\downarrow$$
$$NH_3 \ reacted \ with \ CO_2/H_2O \ to \ yield \ ammonium \ carbonate \ (NH_4)_2CO_3$$
$$\downarrow$$
$$(NH_4)_2CO_3 \ reacted \ with \ NO/NO_2 \ (from \ NH_3 \ oxidation) \ to \ yield \ ammonium \ nitrite \ (NH_4NO_2)$$
$$\downarrow$$
$$NH_3 \ reacted \ with \ SO_2/H_2O \ to \ yield \ ammonium \ bisulphite \ (NH_4HSO_3)$$
$$\downarrow$$
$$NH_4NO_2 \ and \ (NH_4HSO_3) \ reacted \ to \ yield \ hydroxylamine \ disulphonate \ (NOH(SO_3NH_4)_2)$$
$$\downarrow$$
$$(NOH(SO_3NH_4)_2) \ hydrolised \ to \ yield \ hydroxylamine \ sulphate \ ((NH_2OH)_2.H_2SO_4) \ and$$
$$ammonium \ sulphate \ ((NH_4)_2SO_4)$$
$$\downarrow$$
$$Cylohexanone \ reaction:$$
$$C_6H_{10}O \ + \frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3 \ and \ H_2SO_4) \rightarrow C_6H_{10}NOH \ + (NH_4)_2SO_4 \ + H_2O$$
$$\downarrow$$
$$Beckmann \ rearrangement:$$
$$C_6H_{10}NOH \ (+H_2SO_4 \ and \ SO_2) \rightarrow C_6H_{11}NO.H_2SO_4 \ (+4NH_3 \ and \ H_2O) \rightarrow C_6H_{11}NO \ + 2(NH4)_2SO_4$$

In 1999, there were four caprolactam production facilities in the United States. As of 2019, the United States had two companies that produce caprolactam with a total of two caprolactam production facilities: AdvanSix in Virginia (AdvanSix 2020) and BASF in Texas (BASF 2020). Caprolactam production at Fibrant LLC in Georgia ceased in 2018 (Cline 2019).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.4 MMT CO_2 Eq. (5 kt N_2O) in 2019 (see Table 4-33). National emissions from caprolactam production decreased by approximately 18 percent over the period of 1990 through 2019. Emissions in 2019 decreased by approximately 3 percent from the 2018 levels.

Table 4-33: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	1.7	6
2005	2.1	7
2015	1.9	6
2016	1.7	6
2017	1.5	5
2018	1.4	5
2019	1.4	5

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

EPA does not currently estimate the emissions associated with the production of Glyoxal and Glyoxylic Acid due to data availability and a lack of publicly available information on the industry in the United States. See Annex 5 for additional information.

Methodology

Emissions of N_2O from the production of caprolactam were calculated using the estimation methods provided by the *2006 IPCC Guidelines*. The *2006 IPCC Guidelines* Tier 1 method was used to estimate emissions from caprolactam production for 1990 through 2019, as shown in this formula:

$$E_{N_2O} = EF \; x \; CP$$

where,

E_{N_2O}	= Annual N_2O Emissions (kg)
EF	= N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)
CP	= Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The

amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC 2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants. Thus, the 515 thousand metric tons (kt) of caprolactam produced in 2019 (ACC 2020) resulted in N_2O emissions of approximately 1.4 MMT CO_2 Eq. (5 kt).

The activity data for caprolactam production (see Table 4-34) from 1990 to 2019 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2020). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-34: Caprolactam Production (kt)

Year	kt
1990	626
2005	795
2015	700
2016	640
2017	545
2018	530
2019	515

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Uncertainty and Time-Series Consistency

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-35. Nitrous oxide emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production for 2019 were estimated to be between 1.0 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 32 percent above the 2019 emission estimate of 1.4 MMT CO_2 Eq.

Table 4-35: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]	
			(MMT CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.4	1.0	1.8	-31%	+32%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA will also research the production process and emissions associated with the production of glyoxal and glyoxylic acid. During the Expert Review period for the current Inventory report, EPA continues to seek expert solicitation on data available for these emission source categories. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10   Carbide Production and Consumption (CRF Source Category 2B5)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive, metallurgical and other non-abrasive applications in the United States. Emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the Energy chapter.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent of the carbon contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO\ (+\ O_2 \rightarrow 2CO_2)$$
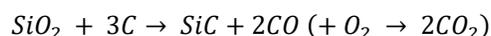
Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. As noted in Annex 5 to this report, CH_4 emissions from calcium carbide production are not estimated because data are not available. EPA is continuing to investigate the inclusion of these emissions in future Inventory reports.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. The U.S. Geological Survey (USGS) reports that a portion (approximately 50 percent) of SiC is used in metallurgical and

other non-abrasive applications, primarily in iron and steel production (USGS 1991a through 2017). As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Demand for SiC consumption in the United States has recovered somewhat from its low in 2009 (USGS 1991a through 2015). Abrasive-grade silicon carbide was manufactured at one facility in 2017 in the United States (USGS 2020).

Carbon dioxide emissions from SiC production and consumption in 2019 were 0.2 MMT CO_2 Eq. (175 kt CO_2) (see Table 4-36 and Table 4-37). Approximately 52 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2019 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4) (see Table 4-36 and Table 4-37). Emissions have not fluctuated greatly in recent years, but 2019 emissions are about 50 percent lower than emissions in 1990.

Table 4-36: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990		2005		2015	2016	2017	2018	2019
CO_2	0.4		0.2		0.2	0.2	0.2	0.2	0.2
CH_4	+		+		+	+	+	+	+
Total	0.4		0.2		0.2	0.2	0.2	0.2	0.2

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-37: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990		2005		2015	2016	2017	2018	2019
CO_2	370		213		176	170	181	184	175
CH_4	1		+		+	+	+	+	+

+ Does not exceed 0.5 kt

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated[39] using the Tier 1 method provided by the *2006 IPCC Guidelines*. Annual estimates of SiC production were multiplied by the appropriate emission factor, as shown below:

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1 \; metric \; ton}{1000 \; kg} \right)$$

where,

$E_{sc,CO2}$	=	CO_2 emissions from production of SiC, metric tons
$EF_{sc,CO2}$	=	Emission factor for production of SiC, metric ton CO_2/metric ton SiC
Q_{sc}	=	Quantity of SiC produced, metric tons
$E_{sc,CH4}$	=	CH_4 emissions from production of SiC, metric tons
$EF_{sc,CH4}$	=	Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

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[39] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data for metallurgical and other non-abrasive applications of SiC are not available; therefore, both CO_2 and CH_4 estimates for SiC are based solely upon production data for SiC for industrial abrasive applications.

Silicon carbide industrial abrasives production data for 1990 through 2013 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2015). Production data for 2014 through 2017 were obtained from the *Mineral Commodity Summaries: Abrasives (Manufactured)* (USGS 2019). Production data for 2018 and 2019 were obtained from the *Mineral Industry Surveys, Manufactured Abrasives* (USGS 2019a, USGS 2020a). Silicon carbide production data obtained through the USGS National Minerals Information Center has been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. SiC consumption for the entire time series is estimated using USGS consumption data (USGS 1991b through 2015, USGS 2017c) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC provided by the U.S. Census Bureau (2005 through 2020) (see Table 4-38). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC by the annual total of national SiC production and net imports.

Emissions of CO_2 from SiC consumption for metallurgical uses were calculated by multiplying the annual utilization of SiC for metallurgical uses (reported annually in the USGS *Minerals Yearbook: Silicon*) by the carbon content of SiC (30.0 percent), which was determined according to the molecular weight ratio of SiC. USGS has not published consumption data for metallurgical uses since 2016 due to concerns of disclosing company-specific sensitive information, and there is uncertainty about the future availability of these data from the USGS. Other options are being explored that would allow the estimation of SiC consumption for metallurgical uses. The 2016 consumption data will be used as a proxy until a suitable approach is developed.

Emissions of CO_2 from SiC consumption for other non-abrasive uses were calculated by multiplying the annual SiC consumption for non-abrasive uses by the carbon content of SiC (30 percent). The annual SiC consumption for non-abrasive uses was calculated by multiplying the annual SiC consumption (production plus net imports) by the percentage used in metallurgical and other non-abrasive uses (50 percent) (USGS 1991a through 2017) and then subtracting the SiC consumption for metallurgical use.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-38: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
2005	35,000	220,149
2015	35,000	153,474
2016	35,000	142,104
2017	35,000	163,492
2018	35,000	168,526
2019	35,000	152,410

Uncertainty and Time-Series Consistency

There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the

quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. However, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-39. Silicon carbide production and consumption CO_2 emissions from 2019 were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.18 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-39: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.18	0.16	0.19	-9%	+9%
Silicon Carbide Production	CH_4	+	+	+	-9%	+9%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

During annual QC, a transcription error in the molecular weight value for silicon was identified that impacts the percentage of carbon in SiC. This corrected percentage (30 percent) was applied to the entire time series for SiC consumption. This change resulted in annual emissions decreases ranging from 3 to 9 kt CO_2 between 1990 and 2018.

4.11   Titanium Dioxide Production (CRF Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide

(CO$_2$). Emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for in the Energy chapter. The chloride process is based on the following chemical reactions:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$
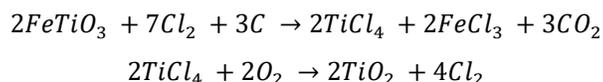
The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO$_2$.

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and FeTiO$_3$ (rutile ore) to form CO$_2$. Since 2004, all TiO$_2$ produced in the United States has been produced using the chloride process, and a special grade of "calcined" petroleum coke is manufactured specifically for this purpose.

The principal use of TiO$_2$ is as a pigment in white paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2019, U.S. TiO$_2$ production totaled 1,100,000 metric tons (USGS 2020). There were five plants producing TiO$_2$ in the United States in 2019.

Emissions of CO$_2$ from titanium dioxide production in 2019 were estimated to be 1.5 MMT CO$_2$ Eq. (1,474 kt CO$_2$), which represents an increase of 23 percent since 1990 (see Table 4-40). Compared to 2018, emissions from titanium dioxide production decreased by 4 percent in 2019, likely due to a 4 percent decrease in production.

Table 4-40: CO$_2$ Emissions from Titanium Dioxide (MMT CO$_2$ Eq. and kt)

Year	MMT CO$_2$ Eq.	Kt
1990	1.2	1,195
2005	1.8	1,755
2015	1.6	1,635
2016	1.7	1,662
2017	1.7	1,688
2018	1.5	1,541
2019	1.5	1,474

Methodology

Emissions of CO$_2$ from TiO$_2$ production were calculated by multiplying annual national TiO$_2$ production by chloride process-specific emission factors using a Tier 1 approach provided in *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E$_{td}$	=	CO$_2$ emissions from TiO$_2$ production, metric tons
EF$_{td}$	=	Emission factor (chloride process), metric ton CO$_2$/metric ton TiO$_2$
Q$_{td}$	=	Quantity of TiO$_2$ produced

The petroleum coke portion of the total CO$_2$ process emissions from TiO$_2$ production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO$_2$ from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO$_2$ from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2013 (see Table 4-41) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2015). Production data for 2014 through 2019 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2020).[40] Data on the percentage of total TiO_2 production capacity that is chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated based on a discussion with Joseph Gambogi (2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-41: Titanium Dioxide Production (kt)

Year	kt
1990	979
2005	1,310
2015	1,220
2016	1,240
2017	1,260
2018	1,150
2019	1,100

Uncertainty and Time-Series Consistency

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates varies from 67 to 100 percent of TiO_2 pigment plants over the time series.

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2

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[40] EPA has not integrated aggregated facility-level GHGRP information for Titanium Dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Titanium dioxide consumption CO_2 emissions from 2019 were estimated to be between 1.3 and 1.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.5	1.3	1.7	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[41] This planned improvement is ongoing and has not been incorporated into this Inventory report. This is a long-term planned improvement.

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[41] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.12 Soda Ash Production (CRF Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. Emissions from soda ash consumption in chemical production processes are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4), and emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for in the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$
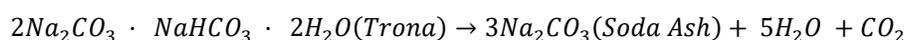
Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.3, Glass Production (CRF Source Category 2A3). In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2020a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming, due to specifics regarding the production processes employed in the state.[42] Based on 2019 reported data, the estimated distribution of soda ash by end-use in 2019 (excluding glass production) was chemical production, 55 percent; other uses, 14 percent; soap and detergent manufacturing, 11 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; flue gas desulfurization, 6 percent; water treatment, 2 percent, and pulp and paper production, 2 percent (USGS 2020b).[43]

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and the majority of the world output of soda ash is made synthetically. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

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[42] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[43] Percentages may not add up to 100 percent due to independent rounding.

In 2019, CO_2 emissions from the production of soda ash from trona ore were 1.8 MMT CO_2 Eq. (1,792 kt CO_2) (see Table 4-43). Total emissions from soda ash production in 2019 increased by approximately 5 percent from emissions in 2018 and have increased by approximately 25 percent from 1990 levels.

Emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry continued a trend of increased production and value in 2019 since experiencing a decline in domestic and export sales caused by adverse global economic conditions in 2009.

Table 4-43: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and kt CO_2)

Year	MMT CO_2 Eq.	kt CO_2
1990	1.4	1,431
2005	1.7	1,655
2015	1.7	1,714
2016	1.7	1,723
2017	1.8	1,753
2018	1.7	1,714
2019	1.8	1,792

Methodology

During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 10.27 metric tons of trona ore are required to generate one metric ton of CO_2, or an emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore (IPCC 2006). Thus, the 18.4 million metric tons of trona ore mined in 2019 for soda ash production (USGS 2020b) resulted in CO_2 emissions of approximately 1.8 MMT CO_2 Eq. (1,792 kt).

Once produced, most soda ash is consumed in chemical production, with minor amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. Consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, emissions from soda ash consumption in chemical production processes are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4).

Data is not currently available for the quantity of trona used in soda ash production. Trona ore produced is used primarily for soda ash production, and for the current Inventory report, EPA assumes that all trona produced was used in soda ash production. The activity data for trona ore production (see Table 4-44) for 1990 through 2019 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020b). Soda ash production[44] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the Soda Ash Production source category consistent with IPCC[45] and UNFCCC guidelines.

[44] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[45] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Table 4-44: Trona Ore Use (kt)

Year	Useª
1990	14,700
2005	17,000
2015	17,600
2016	17,700
2017	18,000
2018	17,600
2019	18,400

ª Trona ore use is assumed to be equal to trona ore production.

Uncertainty and Time-Series Consistency

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2020b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-45. Soda ash production CO_2 emissions for 2019 were estimated to be between 1.5 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.8 MMT CO_2 Eq.

Table 4-45: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimateª			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.8	1.5	1.8	-9%	+8%

ª Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

EPA plans to review USGS data to improve use of activity data to estimate emissions, consistent with the methodological decision trees in *2006 IPCC Guidelines*. EPA also plans to use GHGRP data for conducting category-specific QC of emission estimates, consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[46] This planned improvement is ongoing and has not been incorporated into this Inventory report. This is a medium-term planned improvement and expected to be completed by the next (i.e., 2021) Inventory submission.

4.13 Petrochemical Production (CRF Source Category 2B8)

The production of some petrochemicals results in the release of carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Carbon dioxide emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of methanol and acrylonitrile are presented here and reported under IPCC Source Category 2B8. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for in the Energy sector. The allocation and reporting of emissions from feedstocks transferred out of the system for use in energy purposes to the Energy chapter is consistent with the *2006 IPCC Guidelines*.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 emissions are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use

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[46] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow\ C_2H_4 +\ H_2$$
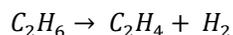
Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the "balanced process"); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 +\ 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$
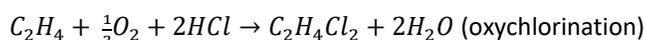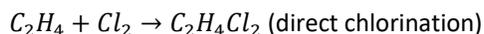
In addition to the byproduct CO_2 produced from the direction oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane, etc.) that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., "syngas" – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2019 were 30.8 MMT CO_2 Eq. (30,792 kt CO_2) and 0.3 MMT CO_2 Eq. (13 kt CH_4), respectively (see Table 4-46 and Table 4-47). Since 1990, total CO_2 emissions from petrochemical production increased by 42 percent. Carbon dioxide emissions from petrochemical production are driven primarily from ethylene, while CH_4 emissions are mainly from methanol production. Overall emissions from methanol production reached a low in 2011, given declining methanol production; however, emissions have been increasing every year since 2011 and are now 53 percent greater than in 1990 (though still 4 percent less than the peak of 4.0 MMT CO_2 Eq. in 1997) due to a rebound in methanol production.

Table 4-46: CO$_2$ and CH$_4$ Emissions from Petrochemical Production (MMT CO$_2$ Eq.)

Year	1990		2005		2015	2016	2017	2018	2019
Total CO$_2$	**21.6**		**27.4**		**28.1**	**28.3**	**28.9**	**29.3**	**30.8**
Carbon Black	3.4		4.3		3.3	3.2	3.3	3.4	3.3
Ethylene	13.1		19.0		20.1	19.8	20.0	19.4	20.7
Ethylene Dichloride	0.3		0.5		0.4	0.4	0.4	0.4	0.5
Methanol	2.5		0.8		2.1	2.8	2.9	3.5	3.8
Ethylene Oxide	1.1		1.5		1.2	1.1	1.3	1.3	1.4
Acrylonitrile	1.2		1.3		1.1	1.0	1.0	1.3	1.1
Total CH$_4$	**0.2**		**0.1**		**0.2**	**0.2**	**0.3**	**0.3**	**0.3**
Methanol	0.2		0.1		0.2	0.2	0.2	0.3	0.3
Acrylonitrile	+		+		+	+	+	+	+
Total	**21.8**		**27.5**		**28.2**	**28.6**	**29.2**	**29.6**	**31.1**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO$_2$ Eq.

Table 4-47: CO$_2$ and CH$_4$ Emissions from Petrochemical Production (kt)

Year	1990		2005		2015	2016	2017	2018	2019
Total CO$_2$	**21,611**		**27,383**		**28,062**	**28,310**	**28,910**	**29,314**	**30,792**
Carbon Black	3,381		4,269		3,260	3,160	3,330	3,440	3,300
Ethylene	13,126		19,024		20,100	19,800	20,000	19,400	20,700
Ethylene Dichloride	254		455		398	447	412	440	503
Methanol	2,513		821		2,054	2,848	2,878	3,484	3,839
Ethylene Oxide	1,123		1,489		1,200	1,100	1,250	1,300	1,370
Acrylonitrile	1,214		1,325		1,050	955	1,040	1,250	1,080
Total CH$_4$	**9**		**3**		**7**	**10**	**10**	**12**	**13**
Methanol	9		3		7	10	10	12	13
Acrylonitrile	+		+		+	+	+	+	+

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.5 kt CH$_4$.

Methodology

Emissions of CO$_2$ and CH$_4$ were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO$_2$ and CH$_4$ emissions from production of acrylonitrile and methanol,[47] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO$_2$ emissions from production of carbon black, ethylene oxide, ethylene, and ethylene dichloride. The Tier 2 method for petrochemicals is a total feedstock carbon (C) mass balance method used to estimate total CO$_2$ emissions, but it is not applicable for estimating CH$_4$ emissions.

As noted in the *2006 IPCC Guidelines*, the total feedstock C mass balance method (Tier 2) is based on the assumption that all of the C input to the process is converted either into primary and secondary products or into CO$_2$. Further, the guideline states that while the total C mass balance method estimates total C emissions from the process, it does not directly provide an estimate of the amount of the total C emissions emitted as CO$_2$, CH$_4$, or non-CH$_4$ volatile organic compounds (NMVOCs). This method accounts for all the C as CO$_2$, including CH$_4$.

Note, a small subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO$_2$ emissions from process vents and/or stacks from stationary combustion units, these

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[47] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile and methanol production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 from flares are included in aggregated CO_2 results. Preliminary analysis of aggregated annual reports shows that flared CH_4 and N_2O emissions are less than 500 kt CO_2 Eq./year. EPA's GHGRP is still reviewing these data across reported years, and EPA plans to address this more completely in future reports.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2019

Carbon dioxide emissions and national production were aggregated directly from EPA's GHGRP dataset for 2010 through 2019 (EPA 2019, 2020). In 2019, data reported to the GHGRP included CO_2 emissions of 3,300,000 metric tons from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 503,000 metric tons of CO_2 from ethylene dichloride production; and 1,370,000 metric tons of CO_2 from ethylene oxide production. These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, and ethylene oxide.

Since 2010, EPA's GHGRP, under Subpart X, requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) to facilitate verification of reported emissions. Under EPA's GHGRP, most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[48] and assumes that all the carbon input is converted into primary and secondary products, byproducts, or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (IPCC Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

1990 through 2009

Prior to 2010, for each of these 4 types of petrochemical processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production. For carbon black, ethylene, ethylene dichloride, and ethylene oxide carbon dioxide emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i" with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2019). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because

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[48] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC's) *Business of Chemistry* (ACC 2020).

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2019. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2019 were obtained from ACC's *Business of Chemistry* (ACC 2020). EPA is not able to apply the integrated aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Methanol

Carbon dioxide and methane emissions from methanol production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Annual methanol production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2019. Emission factors used to estimate methanol production emissions are as follows:

- 2.3 kg CH_4/metric ton methanol produced
- 0.67 metric tons CO_2/metric ton methanol produced

Annual methanol production data for 1990 through 2019 were obtained from the ACC's *Business of Chemistry* (ACC 2020). EPA is not able to apply the integrated aggregated facility-level GHGRP information for methanol production needed for a Tier 2 approach. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Table 4-48: Production of Selected Petrochemicals (kt)

Chemical	1990		2005		2015	2016	2017	2018	2019
Carbon Black	1,310		1,650		1,220	1,190	1,240	1,280	1,210
Ethylene	16,500		24,000		26,900	26,600	27,800	30,500	32,400
Ethylene Dichloride	6,280		11,300		11,300	11,700	12,400	12,500	12,600
Ethylene Oxide	2,430		3,220		3,240	3,270	3,350	3,310	3,800
Acrylonitrile	1,210		1,330		1,050	960	1,040	1,250	1,080
Methanol	3,750		1,230		3,070	4,250	4,300	5,200	5,730

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[49] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are modified to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Uncertainty and Time-Series Consistency

The CH_4 and CO_2 emission factors used for acrylonitrile and methanol production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current Inventory report.

The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, and ethylene oxide are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Petrochemical production CO_2 emissions from 2019 were estimated to be between 29.1 and 32.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below to 6 percent above the emission estimate of 30.8 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2019 were estimated to be between 0.12 and 0.41 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 57 percent below to 47 percent above the emission estimate of 0.3 MMT CO_2 Eq.

Table 4-49: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	30.8	29.1	32.5	-6%	+6%
Petrochemical Production	CH_4	0.3	0.12	0.41	-57%	+47%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019.

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[49] See <https://www.epa.gov/ghgreporting/historical-rulemakings>.

QA/QC and Verification

For Petrochemical Production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).[50] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[51] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride, and ethylene oxide it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions typically are within 5 percent of the emissions calculated using the Tier 1 approach (except for 2018 and 2019 when the differences were 18 percent and 17 percent, respectively). For ethylene dichloride, the GHGRP emissions are typically within 25 percent of the Tier 1 emissions. For ethylene oxide, GHGRP emissions vary from 17 percent less than the Tier 1 emissions to 20 percent more than the Tier 1 emissions, depending on the year.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP, and the sum of reported CH_4 emissions from combustion in stationary combustion units and flares at all of these facilities is on the same order of magnitude as the combined CH_4 emissions presented in this chapter from methanol and acrylonitrile production. The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units).

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[50] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[51] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the inventory.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 500 kt/yr, which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness.

Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

The 2018 data for production and emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide have been updated with updated GHGRP data for 2018 for this Inventory (EPA 2020). These changes resulted in a 0.4 percent decrease in total petrochemical emissions for 2018, compared to the previous Inventory.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of ways to use CH_4 data from the GHGRP in the Inventory. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete this analysis of activity data, emissions, and emission factors and remains a priority improvement within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the Inventory. Some degree of double counting may occur between CO_2 estimates of non-energy use of fuels in the energy sector and CO_2 process emissions from petrochemical production in this sector. This is not considered to be a significant issue since the non-energy use industrial release data includes different categories of sources than those included in this sector. As noted previously in the methodology section, data integration is not feasible at this time as feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. As described in the methodology section of this source category, EPA is currently unable to use GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers, only feedstock type, due to the data failing GHGRP CBI aggregation criteria. Incorporating this data into future Inventories will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current Inventory.

4.14 HCFC-22 Production (CRF Source Category 2B9a)

Trifluoromethane (HFC-23 or CHF_3) is generated as a byproduct during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[52] Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2019. Emissions of HFC-23 from this activity in 2019 were estimated to be 3.7 MMT CO_2 Eq. (0.3 kt) (see Table 4-50). This quantity represents a 13 percent increase from 2018 emissions and a 92 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The increase from 2018 emissions was caused primarily by an increase in the HFC-23 emission rate at one plant. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

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[52] As construed, interpreted, and applied in the terms and conditions of the Montreal Protocol on Substances that Deplete the Ozone Layer [42 U.S.C. §7671m(b), CAA §614].

Table 4-50: HFC-23 Emissions from HCFC-22 Production (MMT CO$_2$ Eq. and kt HFC-23)

Year	MMT CO$_2$ Eq.	kt HFC-23
1990	46.1	3
2005	20.0	1
2015	4.3	0.3
2016	2.8	0.2
2017	5.2	0.3
2018	3.3	0.2
2019	3.7	0.3

Methodology

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used. Emissions for 2010 through 2019 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2019 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected, and also for plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-51.

Table 4-51: HCFC-22 Production (kt)

Year	kt
1990	139
2005	156
2012	96
2013-2019	C

C (CBI)

Note: HCFC-22 production in 2013 through 2019 is considered Confidential Business Information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty and Time-Series Consistency

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo Stochastic Simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo Stochastic Simulation for 2006 were applied to the U.S. emission estimate for 2019. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2019 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-52. HFC-23 emissions from HCFC-22 production were estimated to be between 3.5 and 4.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 3.7 MMT CO_2 Eq.

Table 4-52: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	3.7	3.5	4.1	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019. See Methods discussion of this section above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[53] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

4.15   Carbon Dioxide Consumption (CRF Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled "Carbon Dioxide Transport, Injection, and Geological Storage" and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2019, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 4.9 MMT CO_2 Eq. (4,870 kt) (see Table 4-53). This is an 18 percent increase (740 kt) from 2018 levels and is an increase of approximately 231 percent since 1990.

Table 4-53: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,472
2005	1.4	1,375

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[53] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Year	MMT CO$_2$ Eq.	kt
2015	4.9	4,940
2016	4.6	4,640
2017	4.6	4,580
2018	4.1	4,130
2019	4.9	4,870

Methodology

Carbon dioxide emission estimates for 1990 through 2019 were based on the quantity of CO$_2$ extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO$_2$ produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food production). It is assumed that 100 percent of the CO$_2$ production used in commercial applications other than EOR is eventually released into the atmosphere.

2010 through 2019

For 2010 through 2019, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the Inventory (EPA 2020). Facilities report CO$_2$ extracted or produced from natural reservoirs and industrial sites, and CO$_2$ captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO$_2$ transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO$_2$ transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO$_2$ that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO$_2$ extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98.[54] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2019 is much higher (ranging from 44 to 53) than the number of facilities included in the Inventory for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO$_2$ transferred to end-use applications from naturally occurring CO$_2$ reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO$_2$ production data from four naturally-occurring CO$_2$ reservoirs were used to estimate annual CO$_2$ emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO$_2$ for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO$_2$ for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990 to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-54). Denbury Resources reported the average CO$_2$ production in units of MMCF CO$_2$ per day for

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[54] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-54: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NA	NA
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NA	NA
2015	NA	NA	NA	NA	64,800[b]	8%
2016	NA	NA	NA	NA	55,900[b]	8%
2017	NA	NA	NA	NA	59,900[b]	8%
2018	NA	NA	NA	NA	58,400[b]	7%
2019	NA	NA	NA	NA	61,300[b]	8%

+ Does not exceed 0.5 percent.

NA (Not Available)

[a] Includes only food & beverage applications.

[b] For 2010 through 2019, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria.

Uncertainty and Time-Series Consistency

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[55]

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-55. Carbon dioxide consumption CO_2 emissions for 2019 were estimated to be between 4.6 and 5.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 4.9 MMT CO_2 Eq.

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[55] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

Table 4-55: Approach 2 Quantitative Uncertainty Estimates for CO$_2$ Emissions from CO$_2$ Consumption (MMT CO$_2$ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO$_2$ Consumption	CO$_2$	4.9	4.6	5.1	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO$_2$ Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[56] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[57] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

For the current Inventory, updated GHGRP Subpart PP data were available for the 2015 through 2018 portion of the time series, resulting in recalculations for each of these years. Data from EPA's GHGRP (Subpart PP) were previously unavailable for use for the years 2015 through 2018, so the emissions estimates for 2015 through 2018 had been held constant from 2014. Compared to the previous Inventory, emissions increased by 10 percent for 2015 (470 kt CO$_2$ Eq.), increased by 4 percent for 2016 (170 kt CO$_2$ Eq.), increased by 2 percent for 2017 (110 kt CO$_2$ Eq.) and decreased by 8 percent for 2018 (340 kt CO$_2$ Eq.).

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[58]

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[56] See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

[57] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

[58] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

These improvements are still in process and will be incorporated into future Inventory reports. These are near- to medium-term improvements.

4.16 Phosphoric Acid Production (CRF Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2020). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). The generation of CO_2, however, is due to the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$
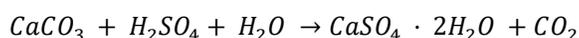
Total U.S. phosphate rock production used in 2019 was an estimated 23.0 million metric tons (USGS 2020). Total imports of phosphate rock to the United States in 2019 were estimated to be approximately 2.0 million metric tons (USGS 2020). Between 2015 and 2018, most of the imported phosphate rock (79 percent) came from Peru, with 20 percent from Morocco and 1 percent from other sources (USGS 2020). All phosphate rock mining companies in the U.S. are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines. The phosphoric acid production facilities that use imported phosphate rock are located in Louisiana.

Over the 1990 to 2019 period, domestic phosphoric acid production has decreased by nearly 54 percent. Total CO_2 emissions from phosphoric acid production were 0.9 MMT CO_2 Eq. (891 kt CO_2) in 2019 (see Table 4-56). Domestic consumption of phosphate rock in 2019 was estimated to have decreased 4 percent relative to 2018 levels (USGS 2020).

Table 4-56: CO₂ Emissions from Phosphoric Acid Production (MMT CO₂ Eq. and kt)

Year	MMT CO₂ Eq.	kt
1990	1.5	1,529
2005	1.3	1,342
2015	1.0	999
2016	1.0	998
2017	1.0	1,028
2018	0.9	940
2019	0.9	891

Methodology

Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium

carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa}	=	CO_2 emissions from phosphoric acid production, metric tons
C_{pr}	=	Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock
Q_{pr}	=	Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product. The United States uses a country-specific methodology consistent with an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock.[59]

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-57). For the years 1990 through 1992, and 2005 through 2019, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina, and the amount mined in Idaho and Utah, are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2019, the same approximation method is used, but data for the share of U.S. production in those states were obtained from the USGS commodity specialist for phosphate rock (USGS 2012). Data for domestic sales or consumption of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2010 were obtained from USGS *Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2015b), and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2020). From 2004 through 2019, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2020).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-58). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

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[59] The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from Phosphoric Acid Production.

Table 4-57: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2015	2016	2017	2018	2019
U.S. Domestic Consumption	49,800	35,200	26,200	26,700	26,300	23,300	23,000
FL and NC	*42,494*	*28,160*	*20,960*	*21,360*	*21,040*	*18,640*	*18,400*
ID and UT	*7,306*	*7,040*	*5,240*	*5,340*	*5,260*	*4,660*	*4,600*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	1,960	1,590	2,470	2,770	2,000
Total U.S. Consumption	**44,011**	**37,830**	**28,160**	**28,290**	**28,770**	**26,070**	**25,000**

Table 4-58: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR (2003a).

Uncertainty and Time-Series Consistency

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2019. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2019 was estimated based on regional production data from 2005 to 2011 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2019 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The Inventory relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process the organic C content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic C in the phosphate rock into CO_2. However, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2017 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2019b). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for

CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-59. 2019 phosphoric acid production CO_2 emissions were estimated to be between 0.8 and 1.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 21 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-59: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.9	0.8	1.1	-19%	+21%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

EPA continues to evaluate potential improvements to the Inventory estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2019 along with assessing applicability of reported GHGRP data to update the inorganic C content of phosphate rock for prior years to ensure time series consistency. Specifically, EPA would need to assess that averaged inorganic C content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic C content (by region or other approaches) from 2010 through 2019, along with other information to inform estimates in prior years in the required time series (1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[60] These long-term planned improvements are still in development by EPA and have not been implemented into the current Inventory report.

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[60] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.17   Iron and Steel Production (CRF Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. Emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for in the Energy chapter.

Iron and steel production includes six distinct production processes: coke production, sinter production, direct reduced iron (DRI) production, pig iron[61] production, electric arc furnace (EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold for use as synthetic natural gas are also included in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

Currently, there are approximately nine integrated iron and steel steelmaking facilities that utilize BOFs to refine and produce steel from iron. As of 2018, these facilities have 21 active blast furnaces between them. Almost 100 steelmaking facilities utilize EAFs to produce steel primarily from recycled ferrous scrap (USGS 2019). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2020). In the United States, four states account for roughly 51 percent of total raw steel production: Indiana, Ohio, Michigan, and Pennsylvania (USGS 2019).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production has slowly and steadily increased for the past few years. The United States was the fourth largest producer of raw steel in the world, behind China, India and Japan, accounting for approximately 4.6 percent of world production in 2019 (AISI 2004 through 2020).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of flux and from the removal of carbon from pig iron used to produce steel.

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[61] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. Therefore, the *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2019 were 1.4 MMT CO_2 Eq. (1,366 kt CO_2) (see Table 4-60 and Table 4-61). Emissions increased slightly in 2019 by 7 percent from 2018 levels and have decreased by 76 percent (4.2 MMT CO_2 Eq.) since 1990. Coke production in 2019 was about 2 percent lower than in 2018 and 51 percent below 1990.

Table 4-60: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990		2005		2015	2016	2017	2018	2019
CO_2	5.6		3.9		4.4	2.6	2.0	1.3	1.4
Total	**5.6**		**3.9**		**4.4**	**2.6**	**2.0**	**1.3**	**1.4**

Table 4-61: CO_2 Emissions from Metallurgical Coke Production (kt)

Gas	1990		2005		2015	2016	2017	2018	2019
CO_2	5,608		3,921		4,417	2,643	1,978	1,282	1,366
Total	**5,608**		**3,921**		**4,417**	**2,643**	**1,978**	**1,282**	**1,366**

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2019 were 39.9 MMT CO_2 Eq. (39,944 kt) and 0.0077 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-62 through Table 4-65), totaling approximately 39.9 MMT CO_2 Eq. Emissions slightly decreased in 2019 from 2018 and have decreased overall since 1990 due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

In 2019, domestic production of pig iron decreased by 7 percent from 2018 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2019 was 53 percent lower than in 2000 and 55 percent below 1990. Carbon dioxide emissions from iron production have decreased by 80 percent since 1990. Carbon dioxide emissions from steel production have decreased by 28 percent (2.2 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 60 percent (59.2 MMT CO_2 Eq.) from 1990 to 2019.

Table 4-62: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990		2005		2015	2016	2017	2018	2019
Sinter Production	2.4		1.7		1.0	0.9	0.9	0.9	0.9

	1990		2005		2015	2016	2017	2018	2019
Iron Production	45.7		17.7		10.3	9.9	8.2	9.6	9.3
Pellet Production	1.8		1.5		1.0	0.9	0.9	0.9	0.9
Steel Production	8.0		9.4		6.9	6.9	6.2	5.8	5.8
Other Activities[a]	41.2		35.9		24.3	22.5	22.4	24.1	23.2
Total	**99.1**		**66.2**		**43.5**	**41.0**	**38.6**	**41.3**	**39.9**

Note: Totals may not sum due to independent rounding.
[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Table 4-63: CO_2 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990		2005		2015	2016	2017	2018	2019
Sinter Production	2,448		1,663		1,016	877	869	937	876
Iron Production	45,701		17,660		10,330	9,928	8,236	9,580	9,273
Pellet Production	1,817		1,503		964	869	867	924	867
Steel Production	7,964		9,395		6,935	6,854	6,218	5,754	5,770
Other Activities [a]	41,194		35,934		24,280	22,451	22,396	24,149	23,158
Total	**99,124**		**66,155**		**43,525**	**40,979**	**38,587**	**41,345**	**39,944**

Note: Totals may not sum due to independent rounding.
[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Table 4-64: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990		2005		2015	2016	2017	2018	2019
Sinter Production	+		+		+	+	+	+	+
Total	**+**		**+**		**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-65: CH_4 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990		2005		2015	2016	2017	2018	2019
Sinter Production	0.9		0.6		0.3	0.3	0.3	0.3	0.3
Total	**0.9**		**0.6**		**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

Methodology

Emission estimates presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). However, sinter production, pellet production and DRI production only account for roughly 8 percent of total iron and steel production emissions and therefore the majority of category emissions are captured with higher tier estimates.

The Tier 2 methodology equation is as follows:

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b) \right] \times \frac{44}{12}$$

where,

E_{CO2}	=	Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons
a	=	Input material a

b	=	Output material b
Q_a	=	Quantity of input material a, metric tons
C_a	=	Carbon content of input material a, metric tons C/metric ton material
Q_b	=	Quantity of output material b, metric tons
C_b	=	Carbon content of output material b, metric tons C/metric ton material
44/12	=	Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$	=	Emissions from sinter production process for pollutant p (CO_2 or CH_4), metric ton
Q_s	=	Quantity of sinter produced, metric tons
$EF_{s,p}$	=	Emission factor for pollutant p (CO_2 or CH_4), metric ton p/metric ton sinter
$E_{d,CO2}$	=	Emissions from DRI production process for CO_2, metric ton
Q_d	=	Quantity of DRI produced, metric tons
$EF_{d,CO2}$	=	Emission factor for CO_2, metric ton CO_2/metric ton DRI
Q_p	=	Quantity of pellets produced, metric tons
$EF_{p,CO2}$	=	Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel, but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-66). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (AISI 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants). Therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-66: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3
[b] Source: EIA (2017c)
[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) (see Table 4-67). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2008) (see Table 4-68). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (AISI 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Currently, data on natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The C content for coke breeze was assumed to equal the C content of coke. Carbon contents for coking coal was from EIA.

Table 4-67: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2015	2016	2017	2018	2019
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	17,879	14,955	15,910	16,635	16,261
Coke Production at Coke Plants	25,054	15,167	12,479	10,755	11,746	12,525	12,215
Coal Breeze Production	2,645	1,594	1,341	1,122	1,193	1,248	1,220
Coal Tar Production	1,058	638	536	449	477	499	488

Table 4-68: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2015	2016	2017	2018	2019
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	84,336	74,807	74,997	80,750	77,692
Natural Gas Consumption	599	2,996	2,338	2,077	2,103	2,275	2,189

Blast Furnace Gas Consumption	24,602	4,460	4,185	3,741	3,683	4,022	3,914

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific C content by each material type (see Table 4-69). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from C contained in inputs such as natural gas, coke oven gas, fluxes (e.g. burnt lime or dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-69). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [AISI 2008]). The amount of flux (e.g., burnt lime or dolomite) used in pig iron production was deducted from the "Other Process Uses of Carbonates" source category (CRF Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-69).

Carbon dioxide emissions associated with the sinter production, direct reduced iron production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-62 and Table 4-63).

Table 4-69: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and
Blast Furnace Gas, Table 1.3.

The production process for sinter results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-70). Although the *1995 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1995) provide a Tier 1 CH_4 emission factor for pig iron production, it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the

estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron also results in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-70: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production and pellet production were estimated by multiplying total national sinter production and the total national direct reduced iron production by Tier 1 CO_2 emission factors (see Table 4-71). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-71: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2019 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2008) (see Table 4-72). In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2017) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2020); however, data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Also, data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2008) (see Table 4-72 and Table 4-73).

Data for EAF steel production, flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2006 through 2016, AISI 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was

provided by AISI (AISI 2008). Data for BOF steel production, flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2008). Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2017). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2020) and through personal communications with AISI (AISI 2008).

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017c) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2020). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2020) and confirmed by AISI staff (Carroll 2016).

Table 4-72: Production and Consumption Data for the Calculation of CO$_2$ and CH$_4$ Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2015	2016	2017	2018	2019
Sinter Production							
Sinter Production	12,239	8,315	5,079	4,385	4,347	4,687	4,378
Direct Reduced Iron Production							
Direct Reduced Iron Production	517	1,303	2,722	C	C	C	C
Pellet Production							
Pellet Production	60,563	50,096	32,146	28,967	28,916	30,793	28,916
Pig Iron Production							
Coke Consumption	24,946	13,832	7,969	7,124	7,101	7,618	7,291
Pig Iron Production	49,669	37,222	25,436	22,293	22,395	24,058	22,302
Direct Injection Coal Consumption	1,485	2,573	2,275	1,935	2,125	2,569	2,465
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,072	1,120	1,127	1,133	1,137
Scrap Steel Consumption	42,691	46,600	44,000	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	49,451	52,589	55,825	58,904	61,172
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	20,300	C	C	C	C
Scrap Steel Consumption	14,713	11,400	4,530	C	C	C	C
Flux Consumption	576	582	454	408	408	408	363
BOF Steel Production	43,973	42,705	29,396	25,888	25,788	27,704	26,591

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Table 4-73: Production and Consumption Data for the Calculation of CO$_2$ Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2015	2016	2017	2018	2019
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	43,294	38,396	38,142	40,204	37,934
Fuel Oil Consumption (thousand gallons)	163,397	16,170	9,326	6,124	4,352	3,365	2,321
Coke Oven Gas Consumption	22,033	16,557	13,921	12,404	12,459	13,337	12,926
Blast Furnace Gas Production	1,439,380	1,299,980	874,670	811,005	808,499	871,860	836,033

EAF Steel Production							
Natural Gas Consumption	15,905	19,985	8,751	3,915	8,105	8,556	9,115
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	386	367	374	405	389
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	70,029	62,036	62,164	67,008	64,377
Blast Furnace Gas Consumption	1,414,778	1,295,520	870,485	807,264	804,816	867,838	832,119

Uncertainty and Time-Series Consistency

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed. Therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average C contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the C contents for pellets, sinter, and natural ore, which are assumed to equal the C contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to "steelmaking furnaces" by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 Inventory report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR. Therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA currently uses an uncertainty range of ±10 percent for the primary data inputs to calculate overall uncertainty from iron and steel production, consistent with *2006 IPCC Guidelines*. During EPA's discussion with AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of

integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-74 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2019 were estimated to be between 33.3 and 49.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 41.3 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2019 were estimated to be between 0.006 and 0.009 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 0.008 MMT CO_2 Eq.

Table 4-74: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	41.3	33.3	49.1	-19%	+19%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-19%	+19%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

No recalculations or changes to calculation methodology were made to the iron and steel production and metallurgical coke production inventory in 2019.

Planned Improvements

Future improvements involve improving activity data and emission factor sources for CO_2 and CH_4 emissions estimations from pellet production. EPA will also evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for this and other Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national

inventories will be relied upon.[62] This is a medium-term improvement and EPA estimates that earliest this improvement could be incorporated is the 2022 Inventory submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development; therefore, it is not included in this current Inventory report and is not expected until a future (i.e., 2022) Inventory submission.

EPA also received comments during the Expert Review cycle of a previous (i.e., 1990 through 2016) Inventory on recommendations to improve the description of the iron and steel industry and emissive processes. EPA began incorporating some of these recommendations into a previous Inventory (i.e., 1990 through 2016) and will require some additional time to implement other substantive changes.

4.18   Ferroalloy Production (CRF Source Category 2C2)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of several ferroalloys. Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). Emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for in the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated. Emissions from the production of ferrochromium and ferromanganese are not included here because of the small number of manufacturers of these materials in the United States, and therefore, government information disclosure rules prevent the publication of production data for these production facilities.

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$
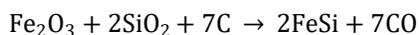
While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Ferroalloys are used primarily by the iron and steel industry, and production trends closely follow that of the iron and steel industry. As of 2016, 11 facilities in the United States produce ferroalloys (USGS 2020).

Emissions of CO_2 from ferroalloy production in 2019 were 1.6 MMT CO_2 Eq. (1,598 kt CO_2) (see Table 4-75 and Table 4-76), which is a 26 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2019 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 34 percent decrease since 1990. These decreases in emissions were mostly caused by the shutdown of two ferroalloy facilities during 2018.

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[62] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

Table 4-75: CO$_2$ and CH$_4$ Emissions from Ferroalloy Production (MMT CO$_2$ Eq.)

Gas	1990	2005	2015	2016	2017	2018	2019
CO$_2$	2.2	1.4	2.0	1.8	2.0	2.1	1.6
CH$_4$	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**2.0**	**1.8**	**2.0**	**2.1**	**1.6**

+ Does not exceed 0.05 MMT CO$_2$ Eq.

Table 4-76: CO$_2$ and CH$_4$ Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2015	2016	2017	2018	2019
CO$_2$	2,152	1,392	1,960	1,796	1,975	2,063	1,598
CH$_4$	1	+	1	1	1	1	+

+ Does not exceed 0.5 kt

Methodology

Emissions of CO$_2$ and CH$_4$ from ferroalloy production were calculated[63] using a Tier 1 method from the *2006 IPCC Guidelines* by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO$_2$ and CH$_4$ emissions are as follows:

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

where,

E_{CO2}	=	CO$_2$ emissions, metric tons
MP_i	=	Production of ferroalloy type i, metric tons
EF_i	=	Generic emission factor for ferroalloy type i, metric tons CO$_2$/metric ton specific ferroalloy product

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4}	=	CH$_4$ emissions, kg
MP_i	=	Production of ferroalloy type i, metric tons
EF_i	=	Generic emission factor for ferroalloy type i, kg CH$_4$/metric ton specific ferroalloy product

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO$_2$ and CH$_4$ estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO$_2$/metric ton of alloy produced, 1.0 kg CH$_4$/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO$_2$/metric ton alloy produced, 1.0 kg CH$_4$/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO$_2$/metric ton metal produced, 1.2 kg CH$_4$/metric ton metal produced.

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[63] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2019 (see Table 4-77) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2015) and the *Mineral Industry Surveys: Silicon* (USGS 2014, 2015b, 2016b, 2017, 2018b, 2019, 2020). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. The production data for 2005 were used as proxy for 2006 through 2010.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production/total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2019 (USGS 2013, 2014, 2015b, 2016b, 2017, 2018b, 2019, 2020).

Table 4-77: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%-55%	Ferrosilicon 56%-95%	Silicon Metal	Misc. Alloys 32-65%
1990	321,385	109,566	145,744	72,442
2005	123,000	86,100	148,000	NA
2015	180,372	159,151	174,477	NA
2016	165,282	145,837	159,881	NA
2017	181,775	160,390	175,835	NA
2018	189,846	167,511	183,642	NA
2019	147,034	129,736	142,229	NA

NA - Not Available for product type, aggregated along with ferrosilicon (25-55% Si)

Uncertainty and Time-Series Consistency

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as proxy for 2005 through 2010). Starting with the *2011 Minerals Yearbook*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories,

based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[64] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-78. Ferroalloy production CO_2 emissions from 2019 were estimated to be between 1.4 and 1.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 2.1 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-78: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.6	1.4	1.8	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

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[64] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[65] This is a long-term planned improvement and EPA is still assessing the possibility of incorporating this improvement into the Inventory. This improvement has not been included in the current Inventory report.

4.19 Aluminum Production (CRF Source Category 2C3)

Aluminum is a light-weight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the twelfth largest producer of primary aluminum, with approximately 1 percent of the world total production (USGS 2019). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.9 MMT CO_2 Eq. (1,880 kt) in 2019 (see Table 4-79). The C anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-79: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq. and kt)

Year	MMT CO₂ Eq.	kt
1990	6.8	6,831
2005	4.1	4,142
2015	2.8	2,767
2016	1.3	1,334
2017	1.2	1,205

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[65] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

2018	1.5	1,451
2019	1.9	1,880

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs) HVAEs cause C from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4, and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have declined by 92 percent and 90 percent, respectively, to 1.4 MMT CO_2 Eq. of CF_4 (0.19 kt) and 0.4 MMT CO_2 Eq. of C_2F_6 (0.03 kt) in 2019 as shown in

Table 4-80 and Table 4-81. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 72 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 70 percent. PFC emissions increased by approximately 8 percent between 2018 and 2019 due to increases in aluminum production. The decrease in the ratio of C_2F_6 to CF_4 emissions between 2018 and 2019 may be due to a combination of a decrease in the measured C_2F_6 to CF_4 weight fraction at some facilities and changes in how production is distributed among facilities with different C_2F_6 to CF_4 weight fractions.

Table 4-80: PFC Emissions from Aluminum Production (MMT CO₂ Eq.)

Year	CF_4	C_2F_6	Total
1990	17.9	3.5	**21.5**
2005	2.9	0.6	**3.4**
2015	1.6	0.5	**2.1**
2016	1.0	0.4	**1.4**
2017	0.7	0.4	**1.1**
2018	1.2	0.4	**1.6**
2019	1.4	0.4	**1.8**

Note: Totals may not sum due to independent rounding.

Table 4-81: PFC Emissions from Aluminum Production (kt)

Year	CF$_4$	C$_2$F$_6$
1990	2.4	0.3
2005	0.4	+
2015	0.2	+
2016	0.1	+
2017	0.1	+
2018	0.2	+
2019	0.2	+

+ Does not exceed 0.05 kt.

In 2019, U.S. primary aluminum production totaled approximately 1.1 million metric tons, a 26 percent increase from 2018 production levels (USAA 2020). In 2019, three companies managed production at seven operational primary aluminum smelters. Two smelters operated at full capacity during 2019, while the other five operated at reduced capacity (USGS 2020). During 2019, monthly U.S. primary aluminum production was higher for every month when compared to the corresponding months in 2018, with the exception of December (USAA 2020).

For 2020, total production for the January to August period was approximately 0.7 million metric tons compared to 0.8 million metric tons for the same period in 2018, a 4.5 percent decrease (USAA 2020). Based on the decrease in production, process CO$_2$ and PFC emissions may be lower in 2020 compared to 2019 if there are no significant changes in process controls at operational facilities.

Methodology

Process CO$_2$ and PFC (i.e., CF$_4$ and C$_2$F$_6$) emission estimates from primary aluminum production for 2010 through 2019 are available from EPA's GHGRP—Subpart F (Aluminum Production) (EPA 2020). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2019) are available to be incorporated into the Inventory. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF$_4$ and C$_2$F$_6$ emissions from anode effects in all prebake and Søderberg electrolysis cells, CO$_2$ emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO$_2$ emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[66] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the Inventory. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO$_2$ from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO$_2$ from Fossil Fuel Combustion.

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[66] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See <https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f>.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$
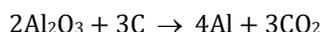
For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all C in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a C consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and 2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2019 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC	=	CF_4 or C_2F_6, kg/MT aluminum
S	=	Slope coefficient, PFC/AE
AE	=	Anode effect, minutes/cell-day
F	=	Anode effect frequency per cell-day
D	=	Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS or USAA, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions.

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2019 based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC

2019). Prior to 2006, LVAE emissions are believed to have been negligible.[67] The following equation was used to estimate LVAE PFC emissions:

$$LVAE\ E_{CF4}\ =\ LVAE\ EF_{CF4}\ \times MP$$

where,

LVAE E_{CF4}	=	LVAE emissions of CF_4 from aluminium production, kg CF_4
LVAE EF_{CF4}	=	LVAE emission factor for CF_4 (default by cell technology type)
MP	=	metal production by cell technology type, tons Al.

LVAE emissions estimates were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on the difference between reporting smelters and national aluminum production levels (USGS and USAA 1990 through 2009), with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2019 were obtained via USAA (USAA 2020). For 1990 through 2001, and 2006 (see Table 4-82) data were obtained from USGS *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002, 2007). For 2002 through 2005, and 2007 through 2019, national aluminum production data were obtained from the USAA's *Primary Aluminum Statistics* (USAA 2004 through 2006, 2008 through 2020).

Table 4-82: Production of Primary Aluminum (kt)

Year	kt
1990	4,048
2005	2,478
2015	1,587
2016	818
2017	741
2018	897
2019	1,126

Uncertainty and Time-Series Consistency

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2019. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6

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[67] The *2019 Refinement* states, "Since 2006, the global aluminium industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximise productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the U.S., as an older technology that has been upgraded.

emission values were determined to have a normal distribution with uncertainty ranges of ±6, ±16, and ±20 percent, respectively.

For the LVAE emission values not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of -10/+7 percent based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-83. Aluminum production-related CO_2 emissions were estimated to be between 1.84 and 1.92 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below to 2 percent above the emission estimate of 1.88 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 1.22 and 1.43 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the emission estimate of 1.33 MMT CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.31 and 0.41 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below to 14 percent above the emission estimate of 0.36 MMT CO_2 Eq.

Table 4-83: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.8	1.8	1.9	-2%	2%
Aluminum Production	CF_4	1.4	1.3	1.5	-8%	8%
Aluminum Production	C_2F_6	0.4	0.3	0.4	-14%	14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[68] Based on the results of the verification process, EPA follows up

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[68] GHGRP Report Verification Factsheet. <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

In a few instances, GHGRP-reporting facilities revised their GHGRP reports due to previously identified reporting errors in 2015 and 2018, resulting in a slight decrease in total emissions of PFCs.

Based on the *2019 Refinement*, Low Voltage Anode Effect (LVAE) emissions were estimated for the years 2006 to 2019 using the Tier 1 production-based methodology (IPCC 2019). The Tier 1 LVAE method uses technology-based default emissions factors, multiplied by metal production. Metal production was estimated based on primary aluminum production capacity. The addition of LVAE emissions estimates resulted in slightly higher CF_4 estimates from 2006 through 2019, with LVAE emissions accounting for 5 percent of total CF_4 emissions in 2019.

4.20   Magnesium Production and Processing (CRF Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. Sulfur hexafluoride has been used in this application around the world for more than thirty years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems.

The magnesium industry emitted 0.9 MMT CO_2 Eq. (0.04 kt) of SF_6, 0.1 MMT CO_2 Eq. (0.05 kt) of HFC-134a, and 0.001 MMT CO_2 Eq. (1.4 kt) of CO_2 in 2019. This represents a decrease of approximately 12 percent from total 2018 emissions (see Table 4-84) and a decrease in SF_6 emissions by 11 percent. In 2019, total HFC-134a emissions decreased from 0.079 MMT CO_2 Eq. to 0.066 MMT CO_2 Eq., or a 16 percent decrease as compared to 2018 emissions. FK 5-1-12 emissions were held constant from 2018. The emissions of the carrier gas, CO_2, decreased from 1.43 kt in 2018 to 1.35 kt in 2019, or 6 percent.

Table 4-84: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2015	2016	2017	2018	2019
SF_6	5.2	2.7	1.0	1.1	1.0	1.0	0.9
HFC-134a	0.0	0.0	0.1	0.1	0.1	0.1	0.1
CO_2	+	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.2**	**2.7**	**1.1**	**1.2**	**1.1**	**1.1**	**1.0**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Table 4-85: SF₆, HFC-134a, FK 5-1-12 and CO₂ Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2015	2016	2017	2018	2019
SF₆	0.2	0.1	+	+	+	+	+
HFC-134a	0.0	0.0	0.1	0.1	0.1	0.1	+
CO₂	1.4	2.9	2.6	2.7	3.1	1.4	1.4
FK 5-1-12 [a]	*0.0*	*0.0*	+	+	+	+	+

+ Does not exceed 0.05 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF₆ Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF₆ emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF₆ consumption, which is assumed to be equivalent to emissions. Along with SF₆, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2019 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF₆, HFC-134a, FK 5-1-12 and CO₂. Consequently, cover and carrier gas emissions from magnesium production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2019 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF₆ emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF₆ per metric ton for 1990 through 1993, and 1.1 kg SF₆ per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF₆ per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF₆ sales to the magnesium sector that was reported in the RAND survey of major SF₆ manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-84. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO₂ carrier gas used for each production type have been estimated using the 1999 estimated CO₂ emissions data and the annual calculated rate of change of SF₆ use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF₆ use between the current year and the subsequent year was

first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year. The emissions of carrier gases for permanent mold, wrought, and anode processes are not estimated in this Inventory.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production are based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999-2001, the sand casting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sand casting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to all other sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b).

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-86.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas and weighted by the cover gases used, was developed for each of the production types. GHGRP data on which these emissions factors are based was available for primary, secondary, die casting and sand casting. The emission factors were applied to the total quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure

time-series consistency. The emissions of carrier gases for permanent mold, wrought, and anode processes are not estimated in this Inventory.

Table 4-86: SF$_6$ Emission Factors (kg SF$_6$ per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF$_6$ per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2019

For 2011 through 2019, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF$_6$ at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF$_6$ emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF$_6$ emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF$_6$ emissions from 2010-2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 2020). USGS data for 2019 was not yet available at the time of the analysis, so the 2017 values were held constant through 2019 as a proxy. Where data was submitted late or with errors or not available for 2019 through the GHGRP, EPA held values constant at previous year's levels for emissions.

Uncertainty and Time-Series Consistency

Uncertainty surrounding the total estimated emissions in 2019 is attributed to the uncertainties around SF$_6$, HFC-134a, and CO$_2$ emission estimates. To estimate the uncertainty surrounding the estimated 2019 SF$_6$ emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2019 through EPA's GHGRP, (2) emissions

estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2019 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation. The uncertainty of the total inventory estimate remained relatively constant between 2018 and 2019.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-87). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-87. Total emissions associated with magnesium production and processing were estimated to be between 0.90 and 1.05 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 8 percent above the 2019 emission estimate of 0.97 MMT CO_2 Eq. The uncertainty estimates for 2019 are similar to the uncertainty reported for 2018 in the previous Inventory.

Table 4-87: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	0.97	0.90	1.05	-8%	8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above and QA/QC and Verification section below.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic

checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[69] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. Note, corrections to the total U.S. activity data for die casting completed for the previous Inventory (see Recalculations Discussion) resolved an apparent increase in the implied emission factor for magnesium production that was caused by recalculations to the diecasting emissions in the 1990 to 2016 Inventory without a concurrent adjustment to the activity data. With both corrections in the Inventory, the implied emission factor for magnesium has a roughly flat trend for 2009 to 2011 and an overall downward trend for 1999 to 2014. There remains a spike in emissions in 2011 partially due to unusually high emissions from two facilities in 2011.

Recalculations Discussion

Die casting and sand volumes were updated based on the release of the 2017 USGS Minerals Yearbook (USGS, 2017). Additionally, one facility's emissions were revised for 2017 and 2018 to reflect its confirmed closure. These revisions resulted in slightly higher emissions in 2017 and reduced emissions in 2018.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the Inventory methodology. Usage and emission details of carrier gases in permanent mold, wrought, and anode processes will be researched as part of a future Inventory. Based on this research and data from a permanent mold facility newly reporting the GHGRP, it will be determined if CO_2 carrier gas emissions are to be estimated.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the Inventory.

4.21   Lead Production (CRF Source Category 2C5)

In 2019, lead was produced in the United States only using secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon dioxide (CO_2) (Sjardin 2003). Emissions from fuels consumed for energy purposes during the production of lead are accounted for in the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the

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[69] GHGRP Report Verification Factsheet. <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

end of 2013. In 2014, the smelter processed a small amount of residual lead during demolition of the site (USGS 2015), and in 2018, the smelter processed no lead (USGS 2016, 2019).

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production has increased in the United States over the past decade, while primary lead production has decreased to production levels of zero. In 2019, secondary lead production accounted for 100 percent of total lead production. The lead-acid battery industry accounted for more than 93 percent of the reported U.S. lead consumption in 2019 (USGS 2020).

In 2019, total secondary lead production in the United States increased from 2018. The United States has become more reliant on imported refined lead in recent years, owing to the closure of the last primary lead smelter in 2013. Exports of spent SLI batteries have been generally decreasing since 2014, however they have increased back up to the 2014 level for 2019 (USGS 2015 through 2020). In the first 10 months of 2019, 22.9 million spent SLI lead-acid batteries were exported, essentially unchanged compared with that in the same time period in 2018 (USGS 2020).

As in 2018, U.S. primary lead production remained at production levels of zero for 2019. This is due to the closure of the only domestic primary lead smelter in 2013 (year-end), as stated previously. In 2019, U.S. secondary lead production was greater than 2018 levels and has increased by 30 percent since 1990 (USGS 1995 through 2020).

In 2019, U.S. lead production totaled 1,200,000 metric tons (USGS 2020). The resulting emissions of CO_2 from 2019 lead production were estimated to be 0.5 MMT CO_2 Eq. (540 kt) (see Table 4-88).

The United States was the fourth largest mine producer of lead in the world, behind China, Australia, and Peru, and accounted for approximately 6 percent of world production in 2019 (USGS 2020).

Table 4-88: CO_2 Emissions from Lead Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	Kt
1990	0.5	516
2005	0.6	553
2015	0.5	473
2016	0.5	500
2017	0.5	513
2018	0.5	513
2019	0.5	540

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000, slightly increased since 2015, and are currently 5 percent higher than 1990 levels.

Methodology

The methods used to estimate emissions for lead production[70] are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

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[70] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

$$CO_2 \; Emissions = (DS \; \times EF_{DS}) \; + (S \; \times EF_S)$$

where,

DS	=	Lead produced by direct smelting, metric ton
S	=	Lead produced from secondary materials
EF_{DS}	=	Emission factor for direct Smelting, metric tons CO_2/metric ton lead product
EF_S	=	Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

The 1990 through 2019 activity data for primary and secondary lead production (see Table 4-89) were obtained from the U.S. Geological Survey (USGS 1995 through 2020).

Table 4-89: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2015	0	1,050,000
2016	0	1,110,000
2017	0	1,140,000
2018	0	1,140,000
2019	0	1,200,000

Uncertainty and Time-Series Consistency

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-90. Lead production CO_2 emissions in 2019 were estimated to be between 0.5 and 0.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below and 16 percent above the emission estimate of 0.5 MMT CO_2 Eq.

Table 4-90: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Lead Production (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO₂	0.5	0.5	0.6	-14%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future Inventory reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

No emissions recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[71]

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[71] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

4.22 Zinc Production (CRF Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). Emissions from fuels consumed for energy purposes during the production of zinc are accounted for in the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Primary production in the United States is conducted through the electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other metallurgical, hydrometallurgical, and pyrometallurgical processes. Worldwide primary zinc production also employs a pyrometallurgical process using the Imperial Smelting Furnace process; however, this process is not used in the United States (Sjardin 2003).

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 2)}$$
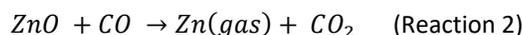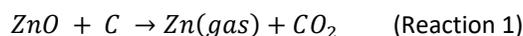
In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

The only companies in the United States that use emissive technology to produce secondary zinc products are American Zinc Recycling (AZR) (formerly "Horsehead Corporation"), Steel Dust Recycling (SDR), and PIZO. For AZR, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The AZR facility in Beaumont, TX also processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine), most of which was transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, AZR permanently shut down their Monaca smelter. This was replaced by their new facility in Mooresboro, NC in 2014.

The new Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). The current capacity of the new facility is 155,000 short tons. Production at the Mooresboro facility was idled in April 2016 and re-started in February 2020, with plans to be at full capacity by 2021 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas have been replaced with electricity consumption at the new Mooresboro facility. The new facility is reported to have a significantly lower greenhouse gas and other air emissions than the Monaca smelter (Horsehead 2012b).

The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR and PIZO recycle EAF dust into intermediate zinc products using Waelz kilns and sell the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2019 were estimated to be 1.0 MMT CO_2 Eq. (1,026 kt CO_2) (see Table 4-91). All 2019 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2019, emissions were estimated to be 62 percent higher than they were in 1990.

Table 4-91: CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.6	632
2005	1.0	1,030
2015	0.9	886
2016	0.8	838
2017	0.9	900
2018	1.0	999
2019	1.0	1,026

In 2019, United States primary and secondary refined zinc production were estimated to total 120,000 metric tons (USGS 2020) (see Table 4-92). Domestic zinc mine production decreased in 2019, owing partially to the closure of the Pend Oreille Mine in Washington State in July after current reserves were exhausted. The mine was reopened in December 2014 after being closed since 2009 (USGS 2020). Primary zinc production (primary slab zinc) in 2018 is used as a proxy for 2019, while secondary zinc production in 2019 increased by 27 percent compared to 2018.

Table 4-92: Zinc Production (Metric Tons)

Year	Primary	Secondary	Total
1990	262,704	95,708	**358,412**
2005	191,120	156,000	**347,120**
2015	122,857	49,143	**172,000**
2016	111,000	15,000	**126,000**
2017	117,000	15,000	**132,000**
2018	101,000	15,000	**116,000**
2019	101,000	19,000	**120,000**

Methodology

The methods used to estimate non-energy CO_2 emissions from zinc production[72] using the electrothermic primary production and Waelz kiln secondary production processes are based on Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO2}	=	CO_2 emissions from zinc production, metric tons
Zn	=	Quantity of zinc produced, metric tons
$EF_{default}$	=	Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1995 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-k: 2005 through 2008 from the 2008 10-k (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-k (Horsehead Corp. 2011); 2011 from the 2011 10-k (Horsehead Corp. 2012a); 2012 from the 2012 10-k (Horsehead Corp. 2013); and 2013 from the 2013 10-k (Horsehead Corp. 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly "Horsehead Corporation") Monaca, PA electrothermic furnace facility. The secondary zinc produced values for

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[72] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2019 were calculated based on the values of EAF dust consumed. The values of EAF dust consumed for AZR, SDR, and PIZO are explained below. The total amount of EAF dust consumed by AZR at their Waelz kilns was available from AZR (formerly "Horsehead Corporation") financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016) and from AZR for 2016, 2017, 2018, and 2019 (AZR 2020). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for AZR's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2019 (SDR 2012, 2014, 2015, 2017, 2018, 2021). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO Technologies Worldwide LLC's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For the current Inventory report, EPA sought expert judgment from the USGS mineral commodity expert to assess approaches for splitting total production into primary and secondary values. For years 2016 through 2019, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2019 total zinc production statistic to estimate secondary zinc production for these years.

Uncertainty and Time-Series Consistency

The uncertainty associated with these estimates is two-fold, relating to activity data and emission factors used.

First, there is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on (1) an EAF dust consumption value reported annually by AZR/Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC) and provided by AZR, and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which is available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010.

Second, there is uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-93. Zinc production CO_2 emissions from 2019 were estimated to be between 0.8 and 1.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 21 percent above the emission estimate of 1.0 MMT CO_2 Eq.

Table 4-93: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	1.0	0.8	1.2	-19%	+21%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Updated data on EAF dust consumed and EAF dust capacity was available for 2015 through 2019 (AZR 2020, PIZO 2021, and SDR 2021). Compared to the previous Inventory, total CO_2 emissions decreased 5 percent (47 kt CO_2) for 2015; 9 percent (87 kt CO_2) for 2016; 11 percent (109 kt CO_2) for 2017, and 1 percent (10 kt CO_2) for 2018.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Zinc Production source category, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[73] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future Inventory reports.

4.23   Electronics Industry (CRF Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRF Source Category 2E1), fluorinated heat transfer fluids (CRF Source Category 2E4) used for temperature control and other applications, and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition (reported under CRF Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRF Source Category 2E5 Other) and photovoltaic cells (CRF Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in plasma etching and chamber cleaning are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this Inventory contains emissions estimates for N_2O and a combination of other HFCs and unsaturated, low-GWP PFCs such as C_5F_8, C_4F_6, HFC-32, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for less than 0.02 percent of emissions (in CO_2 Eq.) from these processes. These gases have been grouped as "other fluorinated gases" for the purpose of this analysis.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the

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[73] See <http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf>.

atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. One percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[74]

For 2019, total GWP-weighted emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes in the U.S. semiconductor industry were estimated to be 4.6 MMT CO_2 Eq. Less than 0.02 percent of total emissions from semiconductor manufacturing consist of a combination of HFCs other than HFC-23 and unsaturated, low-GWP PFCs including C_4F_6, C_4F_8O, C_5F_8, HFC-32, HFC-41, and HFC-134a. These gases have been grouped as "Other F-GHGs". Emissions from all fluorinated greenhouse gases and N_2O are presented in Table 4-94 and Table 4-95 below for the years 1990, 2005, and the period 2015 to 2019. Emissions of F-HTFs that are HFCs, PFCs or SF_6 are presented in Table 4-94. Table 4-96 shows F-HTF emissions in tons by compound group based on reporting to EPA's Greenhouse Gas Reporting Program (GHGRP) during years 2013 through 2019. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

The rapid growth of this industry and the increasing complexity (growing number of layers)[75] of semiconductor products led to an increase in emissions of 153 percent between 1990 and 1999, when emissions peaked at 9.1 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding slightly and more or less plateauing at the current level, which represents a 49 percent decline from 1999 levels. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement

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[74] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the *IPCC Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[75] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 29 percent between 1990 and 2019. Total emissions from semiconductor manufacture in 2019 were slightly lower than 2018 emissions, decreasing by 9 percent. This is likely due in part to reduced production in 2019 as compared to 2018. Increased abatement of F-GHGs also contributed to the decrease in emissions.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, $c\text{-}C_4F_8$, CF_4, HFC-23, NF_3, and SF_6,[76] and were equivalent to only 0.09 percent to 0.34 percent of the total reported emissions from electronics manufacturing in 2011 to 2019. Emissions ranged from 0.0009 to 0.0185 MMT CO_2 Eq. from 1991 to 2019. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total GWP-weighted emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0326 MMT CO_2 Eq. from 1998 to 2019 and were equivalent to between 0.003 percent to 0.67 percent of the total reported emissions from electronics manufacturing. Emissions from manufacturing of photovoltaic cells were estimated based on reported data from a single manufacturer between 2015 and 2017. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, $c\text{-}C_4F_8$, and CHF_3.[77]

Emissions from all fluorinated greenhouse gases from photovoltaic and MEMS manufacturing are in Table 4-94. While EPA has developed an elementary methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emissions.

Only F-HTF emissions that consist of HFC, PFC and SF_6 are included in the Inventory totals; emissions of other F-HTFs, which account for the vast majority of F-HTF emissions, are provided for informational purposes and are not included in the Inventory totals. Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.6 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 13 percent and 19 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from semiconductor manufacturing.[78] Table 4-96 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP during years 2012 through 2019.[79]

Table 4-94: PFC, HFC, SF₆, NF₃, and N₂O Emissions from Electronics Manufacture[80] (MMT CO₂ Eq.)

Year	1990	2005	2015	2016	2017	2018	2019
CF_4	0.8	1.1	1.5	1.5	1.6	1.7	1.6
C_2F_6	2.0	2.0	1.3	1.2	1.2	1.1	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1

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[76] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRF. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[77] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRF. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[78] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2019 were obtained from the EPA GHGRP annual facility emissions reports.

[79] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see <https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276>.

[80] An extremely small portion of emissions included in the totals for Electronics Manufacture are from the manufacturing of MEMS and photovoltaic cells.

	1990		2005		2015	2016	2017	2018	2019
c-C₄F₈	0.0		0.1		0.1	0.1	0.1	0.1	0.1
HFC-23	0.2		0.2		0.3	0.3	0.4	0.4	0.3
SF₆	0.5		0.7		0.7	0.8	0.7	0.8	0.8
NF₃	+		0.5		0.6	0.6	0.6	0.6	0.6
Other F-GHGs	+		+		+	+	+	+	+
Total F-GHGs	**3.6**		**4.6**		**4.7**	**4.7**	**4.6**	**4.8**	**4.3**
N₂O[81]	+		0.1		0.2	0.2	0.3	0.3	0.2
HFC, PFC and SF₆ F-HTFs	0.000		0.012		0.019	0.018	0.021	0.022	0.029
MEMS	0.000		0.013		0.006	0.005	0.006	0.008	0.011
PV	0.000		0.005		0.033	0.029	0.029	0.029	0.029
Total	**3.6**		**4.8**		**5.0**	**5.0**	**4.9**	**5.1**	**4.6**

+ Does not exceed 0.05 MMT CO₂ Eq.

Table 4-95: PFC, HFC, SF₆, NF₃, and N₂O Emissions from Electronics Manufacture (Metric Tons)

Year	1990		2005		2015	2016	2017	2018	2019
CF₄	115		146		206	208	218	232	214
C₂F₆	160		162		110	99	96	92	77
C₃F₈	0		9		16	14	12	12	10
c-C₄F₈	0		11		6	5	6	6	6
HFC-23	15		14		22	23	24	25	21
SF₆	22		31		32	36	31	33	33
NF₃	3		29		33	33	35	36	35
N₂O	120		412		789	792	920	857	755
Total	**435**		**813**		**1,213**	**1,212**	**1,342**	**1,293**	**1,151**

Table 4-96: F-HTF Emissions from Electronics Manufacture by Compound Group (Metric Tons)

Year	2013	2014	2015	2016	2017	2018	2019
HFCs	4.6	2.0	1.6	2.7	1.7	1.7	2.4
PFCs	0.4	0.2	0.3	0.3	0.2	0.4	0.3
SF₆	0.4	0.9	0.6	0.5	0.7	0.6	0.3
HFEs	25.4	25.2	19.0	13.5	16.5	23.3	7.2
PFPMIEs	18.8	18.2	20.8	17.3	14.3	17.7	16.2
Perfluoalkylromorpholines	10.7	10.8	8.1	7.6	5.2	5.9	5.7
Perfluorotrialkylamines	29.5	49.3	43.8	38.6	37.6	40.0	34.4
Total F-HTFs	**89.9**	**106.7**	**94.4**	**80.6**	**76.2**	**89.7**	**66.4**

Table 4-97: F-GHG[a] Emissions from PV and MEMS manufacturing (MMT CO₂ Eq.)

Year	1990		2005		2015	2016	2017	2018	2019
MEMS	0.0		0.013		0.006	0.005	0.006	0.008	0.011
PV	0.0		0.005		0.033	0.029	0.029	0.029	0.029

[a] F-GHGs from PV manufacturing include an unspecified mix of HFCs and PFCs, F-GHGs from MEMS manufacturing includes those gases but also NF₃ and SF₆.

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[81] Emissions of N₂O from semiconductor manufacturing are reported in the CRF under 2H3.

Methodology

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, Partner-reported emissions data received through EPA's PFC[82] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[83]—and estimates of industry activity (i.e., total manufactured layer area). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2019 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2019. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2019. The methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, PV, and HTFs were estimated using the approaches described immediately below.

GHGRP-reported emissions from the manufacturing of MEMS are available for the years 2011 to 2019. Emissions from fabs that reported to the GHGRP as manufacturing MEMS are not included in the semiconductor manufacturing totals reported above. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

GHGRP-reported emissions from the manufacturing of photovoltaic cells are only available between 2015 and 2017 and are from a single manufacturer. These reported emissions are scaled by the ratio of reporters to non-reporters to estimate the total U.S. emissions from PV. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated emissions factor based on GHGRP reported emissions per megawatt from 2015 and 2016. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing,[84] and self-reported capacity by the GHGRP reporter.[85] EPA estimated that during the 2015 to 2017 period, 28 percent of emissions were reported through the GHGRP. These capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2019. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter were scaled to the number of months open in 2014. For 2016 and 2017, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2018 and 2019, emissions were held constant to 2017 estimates, since there is no evidence that much growth has occurred in the U.S. PV cell manufacturing industry in the last two years.

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2019. EPA estimates the emissions of F-HTFs from non-reporting facilities by

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[82] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[83] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

[84] Platzer, Michaela D. (2015) *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support*. Congressional Research Service. January 27, 2015. <https://fas.org/sgp/crs/misc/R42509.pdf>.

[85] DisplaySearch. 2010. DisplaySearch Q4'09 Quarterly FPD Supply/Demand and Capital Spending Report. DisplaySearch, LLC.

calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in electronics manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and 2011 (at 22 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the fluorinated HTF emissions.

1990 through 1994

From 1990 through 1994, Partnership data were unavailable and emissions were modeled using PEVM (Burton and Beizaie 2001).[86] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[87] and (2) product type (discrete, memory or logic).[88] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly-available data on world (including U.S.) silicon consumption.

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[86] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[87] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[88] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, $c\text{-}C_4F_8$, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2018 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions and then these shares were applied to all years prior to reported data from Subpart I (1990 through 2010) and to the emissions from non-reporters from 2011 to 2018.

To estimate N_2O emissions, it is assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions, and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S.

emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[89] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[90, 91, 92]

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[93] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent

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[89] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

[90] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[91] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[92] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[93] EPA considered applying this change to years before 2007, but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

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figure was assumed (SIA 2009).

In addition, publicly-available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[94] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-94. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-94 and Table 4-95 but are shown in Table 4-96 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current Inventory, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the

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[94] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

estimated site-specific DRE,[95] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[96] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[97]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[98] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[99] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

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[95] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[96] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

[97] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[98] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[99] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the Inventory results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the GWP-weighted emissions of that subpopulation.

Gas-specific, GWP-weighted emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 through 2019, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, GWP-weighted emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2019

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2019, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2019 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013.

Historically, partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012 and 2015) (e.g., Semiconductor Materials and Equipment Industry 2017). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2015 and 2016 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, and 2016).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

$$\text{Total Emissions } (E_T) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F\text{-}GHG}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F\text{-}GHG}) + \text{GHGRP Reported N}_2\text{O Emissions } (E_{R,N2O}) + \text{Non-Reporters' Estimated N}_2\text{O Emissions } (E_{NR,N2O})$$

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N_2O, respectively.

The uncertainty in E_T presented in Table 4-98 below results from the convolution of four distributions of emissions, each reflecting separate estimates of possible values of $E_{R,F\text{-}GHG}$, $E_{R,N2O}$, $E_{NR,F\text{-}GHG}$, and $E_{NR,N2O}$. The approach and methods for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) are described in the remainder of this section.

The uncertainty estimate of $E_{R, F\text{-}GHG}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment were developed during the assessment of emission estimation methods for the Subpart I GHGRP rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor

Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[100] The assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not take into account the use of abatement. For the industry segment that processed 200 mm wafers, estimates of uncertainties at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. These gas and wafer-specific uncertainty estimates are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F-GHG}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F-GHG}$).

The uncertainty in $E_{R,N2O}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for

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[100] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults, but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR, F-GHG}$ and $E_{NR, N2O}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For each wafer size for reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The final step in estimating the uncertainty in emissions of reporting and non-reporting facilities is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this final Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a pert beta distribution.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-98, which is also obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility. The emissions estimate for total U.S. F-GHG and N_2O emissions from semiconductor manufacturing were estimated to be between 4.3 and 4.8 MMT CO_2 Eq. at a 95 percent confidence level. This range represents 6 percent below to 6 percent above the 2019 emission estimate of 4.6 MMT CO_2 Eq. for semiconductor emissions for the main seven gases. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table 4-98: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF$_6$, NF$_3$ and N$_2$O Emissions from Semiconductor Manufacture (MMT CO$_2$ Eq. and Percent)[a]

Source	Gas	2019 Emission Estimate (MMT CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO$_2$ Eq.)		(%)	
			Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, SF$_6$, NF$_3$, and N$_2$O	4.6	4.3	4.8	-6%	6%

[a] This uncertainty analysis does not include quantification of the uncertainty of emissions from other F-GHGs for semiconductors, heat transfer fluids, PV, and MEMS.

[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[c] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

It should be noted that the uncertainty analysis for this source category does not quantify the uncertainty of HFC, PFC, and SF$_6$ emissions from the use of heat transfer fluids or the other F-GHGs. While these emissions are included in the semiconductor manufacturing F-GHG total emissions, they make up a small portion of total emissions from the source category (less than 1 percent). Any uncertainty of these emissions would have minimal impact on the overall uncertainty estimates, and therefore the uncertainties associated for HTF HFC, PFC, and SF$_6$ emissions was not included in this analysis for this Inventory year.

Similarly, the uncertainty was not quantified for emissions from the manufacturing of photovoltaics and micro-electro-mechanical devices. These emissions make up a small portion of total emissions from the source category. Any uncertainty of these emissions would have minimal impact on the overall uncertainty estimates, and therefore associated uncertainties were not included.

In an effort to improve the uncertainty analysis for this source category other F-GHGs from semiconductor manufacturing, HFC, PFC, and SF$_6$ emissions from the use of heat transfer fluids and manufacturing of PVs and MEMS may be added in future inventory years (see Planned Improvements section below). The emissions reported under EPA's GHGRP for 2014, 2015, 2016, 2017, 2018, and 2019, which are included in the overall emissions estimates, were based on an updated set of default emission factors.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[101] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Emissions from 2011 through 2019 were updated to reflect updated emissions reporting in EPA's GHGRP, relative to the previous Inventory. Additionally, EPA made the following changes:

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[101] GHGRP Report Verification Factsheet. <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

- Previously, capacity utilization numbers used to develop TMLA estimates for 2015 through 2018 were based on utilizations for quarter four of a given year reported to the U.S. Census Bureau. EPA adjusted this approach to take an average utilization as reported across all four quarters of a reporting year. This minimally affected the emission estimates for non-reporters for F-GHGs and N_2O.
- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this inventory update, EPA identified and made corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.
- As discussed in the Methodology section, emission estimates for 2011 and 2012 were recently updated to take into account the revised emission factors used in 2014 and later years. For this inventory update, EPA identified and made corrections to a few instances where the adjusted emissions used in the regression for developing the non-reporter emission factors were recorded incorrectly.
- EPA updated its approach for adjusting the non-Partner emission factors applied to the 1999-2010 time series to ensure time series consistency. This adjustment is based on a linear interpolation between a PEVM-calculated emission factor from 1999 and an emission factor calculated using 2011 GHGRP-reported data and World Fab Forecast data. EPA updated the 2011 emission factor used to make this adjustment in order to reflect the adjustments made to the 2011 GHGRP reported data in the previous inventory cycle and to ensure time series consistency for data reported through Subpart I. EPA is continuing to evaluate this approach and may make additional improvements per the discussion below.
- Previously, the capacity used to develop emissions estimates from photovoltaics prior to 2012 was estimated using a linear extrapolation between 0 in 1997 and the known U.S. production capacity in 2012. EPA identified a new source of capacity data for 2000 through 2009 and used this data to adjust the estimated emissions between 1997 and 2012. A linear interpolation is now used only for the years between 1997 and 2000, and again between 2009 and 2012.
- For the Monte Carlo simulations the bounds of TMLA, non-reporter emission factors, and reported N_2O emissions are assumed to follow a pert beta distribution given their asymmetry. Previously, these bounds were assumed to be normally distributed.

Planned Improvements

The Inventory methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the understanding of the relationship between the reporting and non-reporting populations is limited. Further analysis of the reporting and non-reporting populations could aid in the accuracy of the non-reporting population extrapolation in future years. In addition, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The Inventory uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2014. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

The current Inventory now includes HFC, PFC, and SF_6 emissions resulting from the use of heat transfer fluids in the total estimates of F-GHG emissions from semiconductor manufacturing. A point of consideration for future Inventory reports is the inclusion of the uncertainty surrounding these emissions in the source category uncertainty analysis (see also Uncertainty and Time-Series Consistency section).

Estimates of non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2019. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent (e.g.,

how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

4.24 Substitution of Ozone Depleting Substances (CRF Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[102] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-99 and Table 4-100.[103]

Table 4-99: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO$_2$ Eq.)

Gas	1990	2005	2015	2016	2017	2018	2019
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	3.9	4.6	5.3	6.0	6.8
HFC-125	+	9.0	43.4	46.9	50.1	53.8	58.5
HFC-134a	+	80.2	73.2	68.8	64.1	61.1	59.8
HFC-143a	+	9.4	27.6	28.2	28.0	27.7	27.8
HFC-236fa	0.0	1.2	1.3	1.3	1.2	1.2	1.1
CF$_4$	0.0	+	+	+	+	0.1	0.1
Others[a]	0.2	7.3	14.0	15.0	15.9	16.3	16.4
Total	**0.2**	**107.3**	**163.6**	**164.9**	**164.7**	**166.1**	**170.6**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO$_2$ Eq.

[a] Others represent an unspecified mix of HFCs and PFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C$_4$F$_{10}$, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C$_6$F$_{14}$.

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[102] [42 U.S.C § 7671, CAA Title VI].

[103] Emissions of ODS are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODS.

Table 4-100: Emissions of HFCs and PFCs from ODS Substitution (Metric Tons)

Gas	1990		2005		2015	2016	2017	2018	2019
HFC-23	0		1		2	2	2	2	2
HFC-32	0		397		5,843	6,801	7,842	8,948	10,094
HFC-125	+		2,580		12,401	13,413	14,327	15,362	16,720
HFC-134a	+		56,052		51,213	48,126	44,797	42,694	41,814
HFC-143a	+		2,093		6,178	6,320	6,264	6,188	6,230
HFC-236fa	0		118		134	129	124	118	112
CF_4	0		2		6	6	6	7	7
Others[a]	M		M		M	M	M	M	M

+ Does not exceed 0.5 MT.

M (Mixture of Gases).

[a] Others represent an unspecified mix of HFCs and PFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[104] In 1993, the use of HFCs in foam production began, and in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 170.6 MMT CO_2 Eq. emitted in 2019. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-101 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2019. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2019 include refrigeration and air-conditioning (133.4 MMT CO_2 Eq., or approximately 78 percent), aerosols (16.3 MMT CO_2 Eq., or approximately 10 percent), and foams (16.1 MMT CO_2 Eq., or approximately 9 percent). Within the refrigeration and air-conditioning end-use sector, large retail food was the highest emitting end-use (33.6 MMT CO_2 Eq.), followed by residential unitary air conditioning. Each of the end-use sectors is described in more detail below.

Table 4-101: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990		2005		2015	2016	2017	2018	2019
Refrigeration/Air Conditioning	+		89.7		124.8	126.5	126.9	129.4	133.4
Aerosols	0.2		10.7		20.8	19.2	17.6	16.0	16.3
Foams	+		4.1		13.9	15.0	15.8	16.2	16.1
Solvents	+		1.7		1.8	1.9	1.9	2.0	2.0
Fire Protection	+		1.1		2.3	2.4	2.5	2.6	2.8
Total	**0.2**		**107.3**		**163.6**	**164.9**	**164.7**	**166.1**	**170.6**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

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[104] R-404A contains HFC-125, HFC-143a, and HFC-134a.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[105] R-404A, and R-507A.[106] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and

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[105] R-410A contains HFC-32 and HFC-125.
[106] R-507A, also called R-507, contains HFC-125 and HFC-143a.

selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as a low-GWP option and 2-BTP is being considered. As fire protection equipment is tested or deployed, emissions of HFCs occur.

Methodology

A detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 78 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Uncertainty and Time-Series Consistency

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 78 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption. Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

The most significant sources of uncertainty for this source category include the charge size for technical aerosols using HFC-134a, as well as total stock of refrigerant installed in industrial process refrigeration and cold storage equipment. For this Inventory year, uncertainty was defined for charge sizes of consumer and technical aerosols, which were assumed to be constant in the uncertainty analysis for previous Inventory reports. The updates to the uncertainty analysis for the aerosols sector resulted in increased overall uncertainty for this source category; however, the results reflect a more robust uncertainty analysis for the consumer and technical aerosol end-uses.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-102. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 164.3 and 192.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3.7 percent below to 13.1 percent above the emission estimate of 170.6 MMT CO_2 Eq.

Table 4-102: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	170.6	164.3	192.9	-3.7%	+13.1%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QC findings are described below.

Comparison of Reported Consumption to Modeled Consumption of HFCs

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[107] was also used to perform quality control as a reference scenario check on the modeled emissions from this source category as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. To do so, consumption patterns demonstrated through data reported under GHGRP Subpart OO—Suppliers of Industrial Greenhouse Gases and Subpart QQ—Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged Equipment or Closed-Cell Foams were compared to the modeled demand for new saturated HFCs (excluding HFC-23) used as ODS substitutes from the Vintaging Model. The collection of data from suppliers of HFCs enables EPA to calculate the reporters' aggregated net supply–the sum of the quantities of chemical produced or imported into the United States less the sum of the quantities of chemical transformed (used as a feedstock in the production of other chemicals), destroyed, or exported from the

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[107] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA (2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

United States.[108] This allows for a quality control check on emissions from this source because the Vintaging Model uses modeled demand for new chemical as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model.

The QA/QC and verification process for individual gases and sources in the Vintaging Model includes regular review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model. The HFCs and PFCs are grouped in the unspecified mix of HFCs and PFCs category only for the purposes of reporting emissions to protect Confidential Business Information (CBI).

Reported Net Supply (GHGRP Top-Down Estimate)

Under EPA's GHGRP, suppliers (i.e., producers, importers, and exporters) of HFCs under Subpart OO began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010) and suppliers of HFCs under Subpart QQ began annually reporting their imports and exports to EPA in 2012 (for supply that occurred in 2011). Beginning in 2015, bulk consumption data for aggregated HFCs reported under Subpart OO were made publicly available under EPA's GHGRP. Data include all saturated HFCs (except HFC-23) reported to EPA across the GHGRP-reporting time series. The data include all 26 such saturated HFCs listed in Table A-1 of 40 CFR Part 98, where regulations for EPA's GHGRP are promulgated, though not all species were reported in each reporting year. For the first time in 2016, net imports of HFCs contained in pre-charged equipment or closed-cell foams reported under Subpart QQ were made publicly available under EPA's GHGRP.

Modeled Consumption (Vintaging Model Bottom-Up Estimate)

The Vintaging Model, used to estimate emissions from this source category, calculates chemical demand based on the quantity of equipment and products sold, serviced and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment and products.[109] It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (often reclaimed) and placed back on the market. In the Vintaging Model, demand for new chemical, as a proxy for consumption, is calculated as any chemical demand (either for new equipment or for servicing existing equipment) that cannot be met through recycled or recovered material. No distinction is made in the Vintaging Model between whether that need is met through domestic production or imports. To calculate emissions, the Vintaging Model estimates the quantity released from equipment over time. Thus, verifying the Vintaging Model's calculated consumption against GHGRP reported data is one way to check the Vintaging Model's emission estimates.

There are eleven saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-43-10mee. For the purposes of this comparison, only ten HFC species are included (HFC-23 is excluded), to more closely align with the aggregated total reported under EPA's GHGRP. While some amounts of less-used saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's GHGRP, the data are believed to represent an amount comparable to the modeled estimates as a quality control check.

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[108] Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

[109] The model builds an inventory of the in-use stock of equipment and products and ODSs and HFCs in each of the sub-applications. Emissions are subsequently estimated by applying annual and disposal emission rates to each population of equipment and products.

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches (i.e., reported and modeled) ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines* (which refer to fluorinated greenhouse gas consumption based on supplies as "potential emissions"):

> [W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006).

Table 4-103 and Figure 4-3 compare the published net supply of saturated HFCs (excluding HFC-23) in MMT CO_2 Eq. as determined from Subpart OO (supply of HFCs in bulk) and Subpart QQ (supply of HFCs in products and foams) of EPA's GHGRP for the years 2010 through 2019 (U.S. EPA 2021a) and the chemical demand as calculated by the Vintaging Model for the same time series.

Table 4-103: U.S. HFC Supply (MMT CO_2 Eq.)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Reported Net Supply (GHGRP)	235	248	245	295	279	290	268	317	338	324
Industrial GHG Suppliers	235	241	227	278	254	264	240	285	304	294
HFCs in Products and Foams[a]	NA	7	18	17	25	26	28	32	34	30
Modeled Supply (Vintaging Model)	265	271	275	281	287	285	288	278	283	278
Percent Difference	13%	9%	12%	-5%	3%	-2%	7%	-12%	-16%	-14%

NA (Not Available)

[a] Importers and exporters of fluorinated gases in products were not required to report 2010 data.

Figure 4-3: U.S. HFC Consumption (MMT CO_2 Eq.)
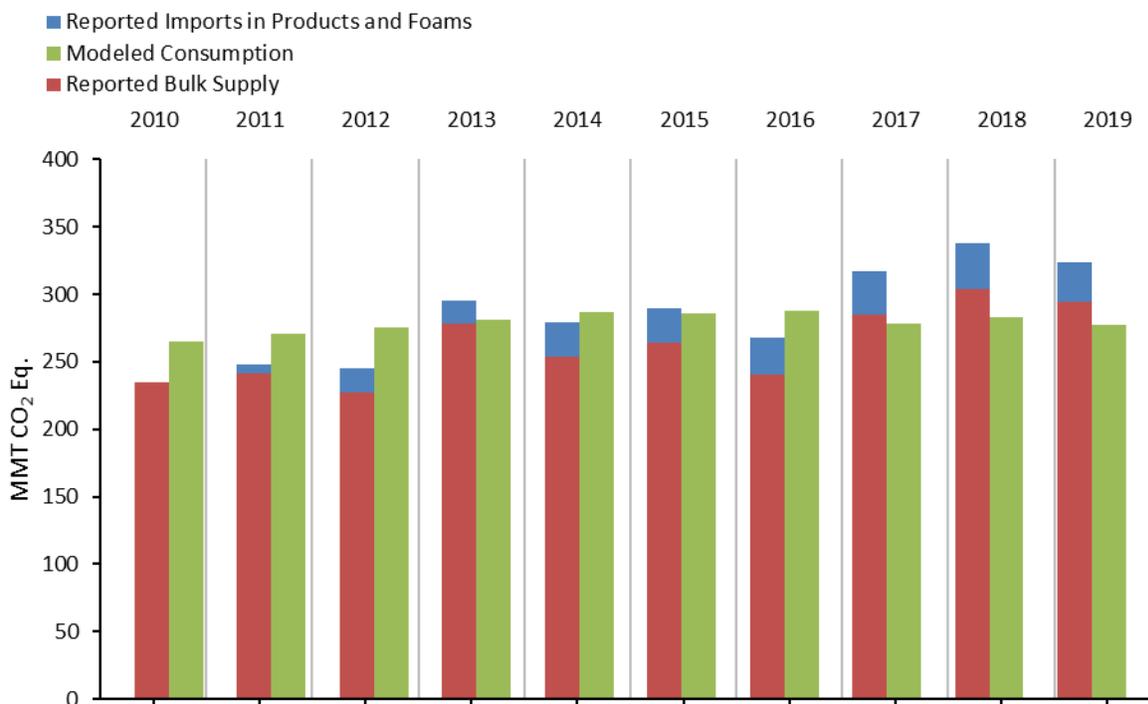
As shown, the estimates from the Vintaging Model are lower than the GHGRP estimates by an average of 0.5 percent across the time series (i.e., 2010 through 2019). Potential reasons for the differences between the reported and modeled data, include:

- The Vintaging Model includes fewer saturated HFCs than are reported to EPA's GHGRP. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP data compared to the modeled estimates would be expected.

- Because the top-down data are reported at the time of actual production or import, and the bottom-up data are calculated at the time of actual placement on the market, there could be a temporal discrepancy when comparing data. Because the GHGRP data and the Vintaging Model estimates generally increase over time (although some year-to-year variations exist), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect.

- An additional temporal effect can result from the stockpiling of chemicals by suppliers and distributors. Suppliers might decide to produce or import additional quantities of HFCs for various reasons such as expectations that prices may increase, or supplies may decrease, in the future. Such stockpiling behavior was seen during ODS phasedowns, but it is unclear if such behavior exists amongst HFC suppliers in anticipation of potential future controls on HFCs. Any such activity would increase the GHGRP data as compared to the modeled data. This effect may be a major reason why the GHGRP data in 2017, 2018, and 2019 are significantly higher than the modeled data.

- Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs or pre-charged equipment and closed-cell foams that contain HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or equal to 25,000 metric tons of CO_2 Eq. per year. Thus, some imports may not be accounted for in the GHGRP data. On the other hand, some exports might also not be accounted for in this data.

- There could be noncompliance with the GHGRP. EPA routinely reviews import data provided by U.S. Customs and Border Protection (CBP) to verify reported supply data and identify facilities that may be subject to the GHGRP. Based on this review and other information, there appear to be companies that imported or exported more than 25,000 metric tons CO_2 Eq. of HFCs annually that have not reported imports or exports to the GHGRP.

- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical or equipment stockpiles as discussed above; in other years, the opposite may hold true. Similarly, relocation of manufacturing facilities or recovery from the recession could contribute to variability in imports or exports. Averaging imports and exports net supplies over multiple years can minimize the impact of such fluctuations. For example, when the 2012 and 2013 net additions to the supply are averaged, as shown in Table 4-104, the percent difference between the consumption estimates decreases compared to the 2012-only and 2013-only estimates.

Table 4-104: Averaged U.S. HFC Demand (MMT CO_2 Eq.)

	2010-2011 Avg.	2011-2012 Avg.	2012-2013 Avg.	2013-2014 Avg.	2014-2015 Avg.	2015-2016 Avg.	2016-2017 Avg.	2017-2018 Avg.	2018-2019 Avg
Reported Net Supply (GHGRP)	242	247	270	287	285	279	293	328	331
Modeled Demand (Vintaging Model)	268	273	278	284	286	287	283	280	280
Percent Difference	11%	11%	3%	-1%	1%	3%	-3%	-14%	-15%

- The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects a slowly increasing overall demand, with some annual fluctuations, actual consumption for specific chemicals or equipment may vary over

time and could even switch from positive to negative (indicating more chemical exported, transformed, and destroyed than produced and imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by disposal recovery. If, in any given year, a significant number of units are disposed, there will be a large amount of additional recovery in that year that can cause an unexpected and not modeled decrease in demand and thus a decrease in consumption. On the other hand, if market, economic, or other factors cause less than expected disposal and recovery, actual supply would decrease, and hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP amounts.

- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, all equipment or products that contain ODS or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like equipment or products originally produced in the United States. The GHGRP data from Subpart OO (industrial greenhouse gas suppliers) includes HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. The GHGRP data from Subpart QQ (supply of HFCs in products) accounts for some of these differences; however, the scope of Subpart QQ does not cover all such equipment or products and the chemical contained therein. Depending on whether the United States is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence for some years possibly higher than GHGRP data:

- Saturated HFCs are also known to be used as a cover gas in the production of magnesium. The Vintaging Model estimates here do not include the amount of HFCs for this use, but rather only the amount for uses that traditionally were served by ODS. Nonetheless, EPA expects this supply not included in the Vintaging Model estimates to be very small compared to the ODS substitute use for the years analyzed. An indication of the different magnitudes of these categories is seen in the fact that the 2019 emissions from that non-modeled source (0.1 MMT CO_2 Eq.) are much smaller than those for the ODS substitute sector (170.6 MMT CO_2 Eq.).

Using a Tier 2 bottom-up modeling methodology to estimate emissions requires assumptions and expert judgment. Comparing the Vintaging Model's estimates to GHGRP-reported estimates, particularly for more widely used chemicals, can help validate the model but it is expected that the model will have limitations. This comparison shows that Vintaging Model consumption estimates are well within the same order of magnitude as the actual consumption data as reported to EPA's GHGRP although the differences in reported net supply and modeled demand are still significant. Although it can be difficult to capture the observed market variability, the Vintaging Model is periodically reviewed and updated to ensure that the model reflects the current and future trajectory of ODS and ODS substitutes across all end-uses and the Vintaging Model will continue to be compared to available top-down estimates in order to ensure the model accurately estimates HFC consumption and emissions.

Recalculations Discussion

For the current Inventory, updates to the Vintaging Model included:

- Updating market size, substitute transitions, and charge size assumptions for Metered Dose Inhaler (MDI) aerosols to align with stakeholder input and market research (EPA 2020i);
- Replacing the commercial refrigeration foam end-use with ten discrete commercial refrigeration application end-uses:
  - Vending machine foam (EPA 2020h),
  - Stand-alone equipment foam (EPA 2020g),

- o Ice machine foam (EPA 2020f),
- o Refrigerated food processing and dispensing equipment foam (EPA 2020e),
- o Small walk-in cooler foam,
- o Large walk-in cooler foam (EPA 2020a),
- o Display case foam (CFC-11) and display case foam (CFC-12) (EPA 2020b),
- o Road transport foam, and
- o Intermodal container foam (EPA 2020c);
- Updating market transitions for the ice maker end-use based on manufacturer information on refrigerant use (EPA 2020d);
- Adjusting manufacturing emissions for domestic refrigerator foam to only include equipment manufactured within the United States, including those that are produced for export, and excluding those that are imported with foam;
- Updating market size, manufacturing loss rate, disposal lost rate, and post-life emission rate assumptions for PU and PIR boardstock foams (EPA 2020j); and
- Updating market size of residential unitary AC, small commercial unitary AC, and large commercial unitary AC to align with AHRI and EIA data (EPA 2021b).

Together, these updates decreased greenhouse gas emissions on average by 0.7 percent between 1990 and 2018.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Fire Suppression sector. Specifically, streaming agent fire suppression lifetimes, market size, and growth rates are under review to align more closely with real world activities. We expect this revision to be prepared for the 2022 or 2023 report. In future reports, EPA also plans to compare atmospheric emissions of select HFCs to the modeled results as an additional QA/QC and Verification analysis.

4.25 Electrical Transmission and Distribution (CRF Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF_6 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 4.2 MMT CO_2 Eq. (0.2 kt) in 2019. This quantity represents an 82 percent decrease from the estimate for 1990 (see Table 4-105 and Table 4-106). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations. Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to less than 2 percent in 2019. A recent examination of the SF_6 emissions reported by electric power systems to EPA's GHGRP revealed that SF_6 emissions from reporters have decreased by 35 percent from 2011 to

2019,[110] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program (Ottinger et al. 2014). Total emissions from electrical transmission and distribution in 2019 were higher than 2018 emissions, increasing by 8.5 percent. The increase in emissions may be attributed to a combination of increasing nameplate capacity and transmission miles in the United States, and an increase in the average emission rate reported to the GHGRP in 2019.

Table 4-105: SF$_6$ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO$_2$ Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	22.8	0.3	**23.2**
2005	7.7	0.7	**8.4**
2015	3.5	0.3	**3.8**
2016	3.8	0.3	**4.1**
2017	3.8	0.3	**4.2**
2018	3.6	0.3	**3.9**
2019	3.9	0.3	**4.2**

Note: Totals may not sum due to independent rounding.

Table 4-106: SF$_6$ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	Emissions
1990	1.0
2005	0.4
2015	0.2
2016	0.2
2017	0.2
2018	0.2
2019	0.2

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[110] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO$_2$ Eq.) for three consecutive years or below 25,000 MT CO$_2$ Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO$_2$ Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

Methodology

The estimates of emissions from Electrical Transmission and Distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 to 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[111] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + nameplate capacity of retiring equipment (kilograms) [112]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 13.6 MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in

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[111] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

[112] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2019 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2019 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); and (3) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), which was applied to the electric power systems that do not report to EPA (Non-Reporters). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

Partners

Over the period from 1999 to 2019, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[113] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2019, approximately 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 96 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2019 data accounted for approximately 3 percent of the total emissions attributed to Partner utilities.[114]

The GHGRP program has an "offramp" provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate. After three consecutive years of non-reporting, they are treated as non-reporters, as described in the section below on non-reporters. Partners that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

GHGRP-Only Reporters

EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under

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[113] Starting in the 1990 to 2015 Inventory, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[114] Only data reported as of September 28, 2020 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

the Partnership.) As under the Partnership, electric power systems that report their SF$_6$ emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. Many Partners began reporting their emissions through EPA's GHGRP in 2012 (reporting emissions for 2011 and later years) because their nameplate capacity exceeded the reporting threshold. Some Partners who did not report through EPA's GHGRP continued to report through the Partnership.

In addition, many non-Partners began reporting to EPA for the first time through its GHGRP in 2012. Non-Partner emissions reported and verified under EPA's GHGRP were compiled to form a new category of reported data (GHGRP-Only Reporters). GHGRP-Only Reporters accounted for 21 percent of U.S. transmission miles and 24 percent of estimated U.S. emissions from electric power system in 2019.[115]

Emissions for GHGRP-only reporters that off-ramp are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate. After three consecutive years of non-reporting, they are treated as non-reporters, and emissions are subsequently estimated based on the methodology described below.

Non-Reporters

Emissions from Non-Reporters (i.e., utilities other than Partners and GHGRP-Only Reporters) in every year since 1999 were estimated using the results of a regression analysis that correlated emissions from reporting utilities (using verified data from both Partners and GHGRP-Only Reporters) with their transmission miles.[116] As noted above, non-Partner emissions were reported to the EPA for the first time through its GHGRP in 2012 (representing 2011 emissions). This set of reported data was of particular interest because it provided insight into the emission rate of non-Partners, which previously was assumed to be equal to the historical (1999) emission rate of Partners. Specifically, emissions were estimated for Non-Reporters as follows:

- Non-Reporters, 1999 to 2011: First, the 2011 emission rates (per kg nameplate capacity and per transmission mile) reported by Partners and GHGRP-Only Reporters were reviewed to determine whether there was a statistically significant difference between these two groups. Transmission mileage data for 2011 was reported through GHGRP, with the exception of transmission mileage data for Partners that did not report through GHGRP, which was obtained from UDI. It was determined that there is no statistically significant difference between the emission rates of Partners and GHGRP-Only reporters; therefore, Partner and GHGRP-Only reported data for 2011 were combined to develop regression equations to estimate the emissions of Non-Reporters. Historical emissions from Non-Reporters were estimated by linearly interpolating between the 1999 regression coefficient (based on 1999 Partner data) and the 2011 regression coefficient.

- Non-Reporters, 2012 to Present: It was determined that there continued to be no statistically significant difference between the emission rates reported by Partners and by GHGRP-Only Reporters. Therefore, the emissions data from both groups were combined to develop regression equations for 2012. This was repeated for 2013 through 2019 using Partner and GHGRP-Only Reporter data for each year.

  o The 2019 regression equation for reporters was developed based on the emissions reported by a subset of Partner utilities and GHGRP-Only utilities who reported non-zero emissions and non-zero transmission miles (representing approximately 65 percent of total U.S. transmission miles). The regression equation for 2019 is:

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[115] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[116] In the United States, SF$_6$ is contained primarily in transmission equipment rated above 34.5 kV.

$$\text{Emissions (kg)} = 0.226 \times \text{Transmission Miles}$$

Table 4-107 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for 1999 (the first year data was reported), and for 2011 through present (the years with GHGRP reported data). The coefficient increased between 2015 and 2019.

Table 4-107: Transmission Mile Coverage (Percent) and Regression Coefficients (kg per mile)

	1999		2005		2015	2016	2017	2018	2019
Percentage of Miles Covered by Reporters	50%		50%		73%	73%	74%	70%	65%
Regression Coefficient[a]	0.71		0.35		0.19	0.21	0.24	0.21	0.23

[a] Regression coefficient for emissions is calculated utilizing transmission miles as the explanatory variable and emissions as the response variable. The equation utilizes a constant intercept of zero. When calculating the regression coefficient, outliers are also removed from the analysis when the standard residual for that reporter exceeds the value 3.0.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.5 percent as transmission miles grew yet again by over 30,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2019 was calculated to be 0.6 percent, as transmission miles increased by approximately 43,000 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2019 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, and the non-reporting utilities' emissions (determined using the regression equations).

1990 through 2019 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2019 emissions from original electrical equipment manufacturers (OEMs).

- OEM emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs

through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6 provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.

- OEM emissions from 2011 through 2019 were estimated using the SF_6 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs.

Uncertainty and Time-Series Consistency

To estimate the uncertainty associated with emissions of SF_6 from Electrical Transmission and Distribution, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA's GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 6.0 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 20 percent.[117] Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 8.5 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-108. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 3.6 and 5.0 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 18 percent above the emission estimate of 4.2 MMT CO_2 Eq.

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[117] Uncertainty is assumed to be higher for the GHGRP-Only category, because 2011 is the first year that those utilities have reported to EPA.

Table 4-108: Approach 2 Quantitative Uncertainty Estimates for SF$_6$ Emissions from Electrical Transmission and Distribution (MMT CO$_2$ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO$_2$ Eq.)	Uncertainty Range Relative to 2018 Emission Estimate[a] (MMT CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF$_6$	4.2	3.6	5.0	-16%	+18%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF$_6$ sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF$_6$ appears to reflect the trend in global emissions implied by changing SF$_6$ concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF$_6$ emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF$_6$ that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF$_6$ recycling equipment, stated that most U.S. utilities began recycling rather than venting SF$_6$ within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[118] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

The historical emissions estimated for this source category have undergone the following revisions for the period 1990 through 2018.

- **GHGRP report resubmissions:** Historical estimates for the period 2011 through 2018 were updated relative to the previous report based on revisions to reported historical data in EPA's GHGRP.

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[118] GHGRP Report Verification Factsheet. <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

As a result of the recalculations, SF_6 emissions from electrical transmission and distribution decreased by 3.9 percent for 2018 relative to the previous report, and SF_6 nameplate capacity decreased by 0.3 percent for 2018 relative to the previous report. On average, SF_6 emission estimates for the entire time series decreased by approximately 0.1 percent per year.

Planned Improvements

EPA plans to more closely examine transmission miles data by company provided by the UDI data sets, which has been historically purchased every three years, to identify inconsistencies in the companies included in the data sets and improve the transmission mile estimates to address data gaps, as necessary. In future inventory years, EPA plans to identify additional sources for transmission miles data by company due to a discontinuation of this specific data set in 2017.

Additionally, as the information on the type of new and retiring equipment is collected through GHGRP reporting, EPA expects this data to provide insight into the relative importance of the two types of equipment as potential emission sources. Historically, hermetically sealed pressure equipment has been considered to be a relatively small source of SF_6 in the United States; however, better estimating its potential source of emissions upon end-of-life (i.e., disposal emissions) is an area for further analysis.

EPA also plans to investigate ways in which the electric transmission and distribution sector estimates can be disaggregated to state level emissions estimates in order to provide greater clarity and specificity in emissions rates by region.

4.26   Nitrous Oxide from Product Uses (CRF Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2019 was approximately 15 kt (see Table 4-109).

Table 4-109: N_2O Production (kt)

Year	kt
1990	16
2005	15
2015	15

2016	15
2017	15
2018	15
2019	15

Nitrous oxide emissions were 4.2 MMT CO_2 Eq. (14 kt N_2O) in 2019 (see Table 4-110). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-110: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	4.2	14
2005	4.2	14
2015	4.2	14
2016	4.2	14
2017	4.2	14
2018	4.2	14
2019	4.2	14

Methodology

Emissions from N_2O product uses were estimated using the following equation:

$$E_{pu} = \sum_a (P \times S_a \times ER_a)$$

where,

E_{pu}	=	N_2O emissions from product uses, metric tons
P	=	Total U.S. production of N_2O, metric tons
a	=	specific application
S_a	=	Share of N_2O usage by application *a*
ER_a	=	Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2019, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.23 Electronics Industry (CRF Source Category 2E) and reported under CRF Source Category 2H3. For

the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2003).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for 1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2003). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2003) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2003). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the unavailability of data, production estimates for years 2004 through 2019 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2003). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the unavailability of data, the share of total quantity of N_2O usage data for years 2004 through 2019 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2003). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2003). The emissions rate for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

The overall uncertainty associated with the 2019 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-111. Nitrous oxide emissions from N_2O product usage were estimated to be between 3.2 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 4.2 MMT CO_2 Eq.

Table 4-111: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	4.2	3.2	5.2	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this Inventory. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current Inventory report.

4.27 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various ozone precursors. The reporting requirements of the UNFCCC[119] request that information be provided on precursor greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-CH_4 volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. As some of industrial applications also employ thermal incineration as a control technology, combustion byproducts, such as CO and NO_x, are also reported with this source category. NMVOCs, commonly referred to as

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[119] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

"hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

Accidental releases of greenhouse gases associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in this chapter.

Total emissions of NO_x, CO, and NMVOCs from non-energy industrial processes and product use from 1990 to 2019 are reported in Table 4-112. Sulfur dioxide emissions are presented in Section 2.3 of the Trends chapter and Annex 6.3.

Table 4-112: NO_x, CO, and NMVOC Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
NO_x	**592**	**572**	**408**	**402**	**397**	**397**	**397**
Industrial Processes							
Other Industrial Processes[a]	343	437	297	294	291	291	291
Metals Processing	88	60	62	61	60	60	60
Chemical and Allied Product Manufacturing	152	55	41	39	37	37	37
Storage and Transport	3	15	5	5	5	5	5
Miscellaneous[b]	5	2	2	2	3	3	3
Product Uses							
Surface Coating	1	3	1	1	1	1	1
Graphic Arts	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Other Industrial Processes[a]	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
CO	**4,129**	**1,557**	**1,163**	**1,075**	**1,006**	**1,006**	**1,006**
Industrial Processes							
Metals Processing	2,395	752	510	468	425	425	425
Other Industrial Processes[a]	487	484	488	447	406	406	406
Chemical and Allied Product Manufacturing	1,073	189	114	110	107	107	107
Miscellaneous[b]	101	32	42	42	61	61	61
Storage and Transport	69	97	7	7	7	7	7
Product Uses							
Surface Coating	+	2	1	1	1	1	1
Other Industrial Processes[a]	4	0	0	0	0	0	0
Dry Cleaning	+	0	0	0	0	0	0
Degreasing	+	0	0	0	0	0	0
Graphic Arts	+	0	0	0	0	0	0
Non-Industrial Processes[c]	+	0	0	0	0	0	0
Other	NA	0	0	0	0	0	0
NMVOCs	**7,638**	**5,849**	**3,796**	**3,776**	**3,767**	**3,767**	**3,767**
Industrial Processes							
Storage and Transport	1,352	1,308	619	626	633	633	633
Other Industrial Processes[a]	364	414	314	314	314	314	314
Chemical and Allied Product Manufacturing	575	213	69	69	68	68	68
Miscellaneous[b]	20	17	24	24	35	35	35
Metals Processing	111	45	24	22	20	20	20

Product Uses							
Surface Coating	2,289	1,578	1,124	1,114	1,105	1,105	1,105
Non-Industrial Processes[c]	1,724	1,446	1,030	1,021	1,012	1,012	1,012
Degreasing	675	280	200	198	196	196	196
Dry Cleaning	195	230	164	163	161	161	161
Graphic Arts	249	194	138	137	136	136	136
Other Industrial Processes[a]	85	88	62	62	61	61	61
Other	+	36	26	25	25	25	25

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

[c] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Methodology

Emission estimates for 1990 through 2019 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2020) and disaggregated based on EPA (2003). Data were collected for emissions of CO, NO_x, volatile organic compounds (VOCs), and SO_2 from metals processing, chemical manufacturing, other industrial processes, transport and storage, and miscellaneous sources. Emissions were calculated either for individual source categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed or the amount of solvent purchased) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Emissions for product use were calculated by aggregating product use data based on information relating to product uses from different applications such as degreasing, graphic arts, etc. Emission factors for each consumption category were then applied to the data to estimate emissions. For example, emissions from surface coatings were mostly due to solvent evaporation as the coatings solidify. By applying the appropriate product-specific emission factors to the amount of products used for surface coatings, an estimate of NMVOC emissions was obtained. Emissions of CO and NO_x under product use result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors*, AP-42 (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty and Time-Series Consistency

Uncertainties in these estimates are partly due to the accuracy of the emission factors and activity data used. A quantitative uncertainty analysis was not performed.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) and nitrous oxide (N_2O) emissions from enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in the Energy chapter under the Industrial sector emissions. Methane and N_2O emissions from mobile on-farm energy use are reported in the Energy chapter under mobile fossil fuel combustion emissions.

Figure 5-1: 2019 Agriculture Chapter Greenhouse Gas Emission Sources
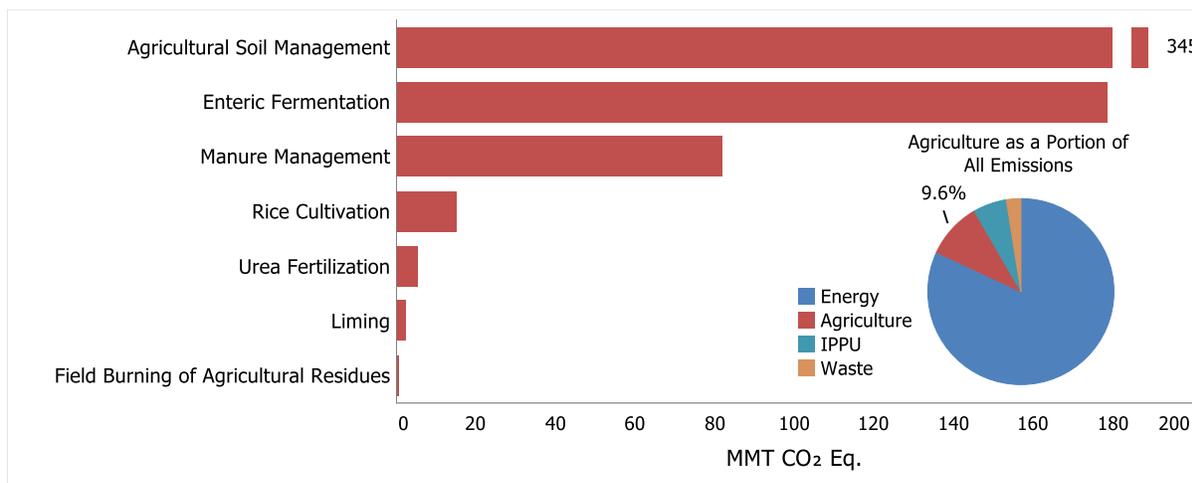
In 2019, the Agriculture sector was responsible for emissions of 628.6 MMT CO_2 Eq.,[1] or 9.6 percent of total U.S. greenhouse gas emissions. Methane emissions from enteric fermentation and manure management represent 27.1 percent and 9.5 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Emissions of N_2O by agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 75.4 percent. Manure management and field burning

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[1] Following the current reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming accounted for 0.10 percent and 0.05 percent of total CO_2 emissions from anthropogenic activities, respectively.

Table 5- and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2019, CO_2 and CH_4 emissions from agricultural activities increased by 9.9 percent and 17.5 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year, but increased by 10.4 percent overall. Trends in sources of agricultural emissions over the 1990 to 2019 time series are shown in Figure 5-2.

Figure 5-2: Trends in Agriculture Chapter Greenhouse Gas Emission Sources
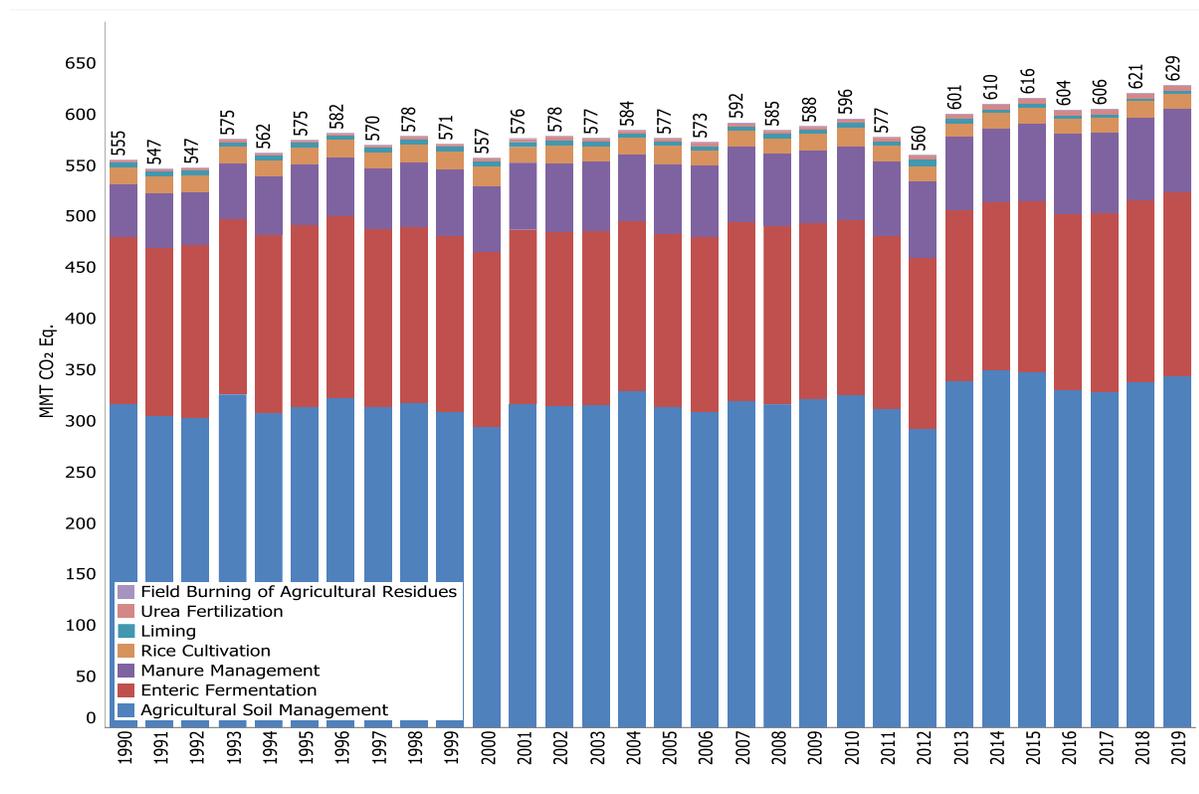
Each year, some emission estimates in the Agriculture sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 through 2018) to ensure that the trend is accurate. This year's notable updates include (1) Enteric Fermentation: default national emission factors were updated for sheep and goats; (2) Field Burning of Agricultural Residues: updated parameters within the methodology for combustion efficiency; (3) Urea Fertilization: updated methodology based on the analytical solution from the Monte Carlo analysis; (4) Rice Cultivation: correction in splicing method; (5) Liming: updated activity data from USGS; and (6) Agricultural Soil Management: using surrogate date method to update the time series of PRP and manure N available for application to soils. In total, the improvements made to the Agriculture sector in this Inventory increased greenhouse gas emissions by 2.5 MMT CO_2 Eq. (0.4 percent) in 2018. For more information on specific methodological updates, please see the Recalculations discussions within the respective source category sections of this chapter.

Emissions reported in the Agriculture chapter include those from all states; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O emissions, are not included (see chapter sections on "Uncertainty and Time-Series Consistency" and "Planned Improvements" for more details). In addition, U.S. Territories and the District of Columbia are not estimated with the exception of Urea Fertilization in Puerto Rico due to incomplete data. EPA continues to review available data on an ongoing basis to include emissions from territories in future inventories to the extent they are occurring. Many U.S.

territories in the Pacific Islands have no permanent populations and therefore EPA assumes no agriculture activities are occuring. See Annex 5 for more information on EPA's assessment of the sources not included in this inventory.

Table 5-1: Emissions from Agriculture (MMT CO$_2$ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO$_2$	**7.1**	**7.9**	**8.5**	**8.0**	**8.1**	**7.4**	**7.8**
Urea Fertilization	2.4	3.5	4.7	4.9	5.1	5.2	5.3
Liming	4.7	4.3	3.7	3.1	3.1	2.2	2.4
CH$_4$	**218.2**	**239.3**	**241.4**	**248.1**	**251.0**	**255.7**	**256.4**
Enteric Fermentation	164.7	169.3	166.9	172.2	175.8	178.0	178.6
Manure Management	37.1	51.6	57.9	59.6	59.9	61.7	62.4
Rice Cultivation	16.0	18.0	16.2	15.8	14.9	15.6	15.1
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N$_2$O	**330.1**	**329.9**	**366.2**	**348.4**	**346.4**	**357.9**	**364.4**
Agricultural Soil Management	315.9	313.4	348.5	330.1	327.6	338.2	344.6
Manure Management	14.0	16.4	17.5	18.1	18.7	19.4	19.6
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**555.3**	**577.1**	**616.1**	**604.4**	**605.5**	**621.0**	**628.6**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CO$_2$	**7,084**	**7,854**	**8,464**	**7,959**	**8,131**	**7,440**	**7,782**
Urea Fertilization	2,417	3,504	4,728	4,877	5,051	5,192	5,341
Liming	4,667	4,349	3,737	3,081	3,080	2,248	2,442
CH$_4$	**8,728**	**9,572**	**9,656**	**9,923**	**10,040**	**10,226**	**10,256**
Enteric Fermentation	6,588	6,772	6,675	6,890	7,032	7,119	7,142
Manure Management	1,485	2,062	2,316	2,385	2,395	2,467	2,495
Rice Cultivation	640	720	648	631	596	623	602
Field Burning of Agricultural Residues	15	17	18	17	17	17	17
N$_2$O	**1,108**	**1,107**	**1,229**	**1,169**	**1,162**	**1,201**	**1,223**
Agricultural Soil Management	1,060	1,052	1,169	1,108	1,099	1,135	1,156
Manure Management	47	55	59	61	63	65	66
Field Burning of Agricultural Residues	1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions provided in the Agriculture chapter do not preclude alternative examinations, but rather, this chapter presents emissions in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to

5.1 Enteric Fermentation (CRF Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.[2]

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2019 were 178.6 MMT CO_2 Eq. (7,142 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2019. Emissions from dairy cattle in 2019 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.[3]

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2015	2016	2017	2018	2019
Beef Cattle	119.1	125.2	118.0	123.0	126.3	128.1	129.1
Dairy Cattle	39.4	37.6	42.6	43.0	43.3	43.6	43.2

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[2] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[3] Enteric fermentation emissions from poultry are not estimated because no IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry; at this time, developing of a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category. Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

	1990		2005		2015	2016	2017	2018	2019
Swine	2.0		2.3		2.6	2.6	2.7	2.8	2.9
Horses	1.0		1.7		1.4	1.4	1.3	1.2	1.1
Sheep	2.6		1.4		1.2	1.2	1.2	1.2	1.2
Goats	0.6		0.7		0.6	0.6	0.6	0.6	0.6
American Bison	0.1		0.4		0.4	0.4	0.4	0.4	0.4
Mules and Asses	+		0.1		0.1	0.1	0.1	0.1	0.1
Total	**164.7**		**169.3**		**166.9**	**172.2**	**175.8**	**178.0**	**178.6**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990		2005		2015	2016	2017	2018	2019
Beef Cattle	4,763		5,007		4,722	4,919	5,052	5,125	5,162
Dairy Cattle	1,574		1,503		1,706	1,722	1,730	1,744	1,729
Swine	81		92		102	105	108	111	115
Horses	40		70		57	54	51	48	46
Sheep	102		55		47	48	47	47	47
Goats	23		26		24	24	24	24	24
American Bison	4		17		14	15	15	15	16
Mules and Asses	1		2		3	3	3	3	3
Total	**6,588**		**6,772**		**6,675**	**6,890**	**7,032**	**7,119**	**7,142**

Note: Totals may not sum due to independent rounding.

From 1990 to 2019, emissions from enteric fermentation have increased by 8.4 percent. From 2018 to 2019, emissions increased by 0.3 percent, largely driven by an increase in beef cattle populations. While emissions generally follow trends in cattle populations, over the long term there are exceptions. For example, while dairy cattle emissions increased 9.8 percent over the entire time series, the population has declined by 3.1 percent, and milk production increased 58 percent (USDA 2019). These trends indicate that while emissions per head are increasing, emissions per unit of product (i.e., meat, milk) are decreasing.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations increased, and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased from 2015 to 2019, consistent with another increase in population over those same years. Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets used by producers across the United States). Dairy cattle emissions have continued to trend upward since 2007, in line with dairy cattle population increases. Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 54 percent since 1990. Horse populations are 15 percent greater than they were in 1990, but their numbers have been declining by an average of 4 percent annually since 2007. Goat populations increased by about 20 percent through 2007, steadily decreased through 2012, then increased again, by about 1 percent annually, through 2019. Swine populations have trended upward through most of the time series, increasing 43 percent from 1990 to 2019. The population of American bison more than tripled over the 1990 to 2019 time period, while the population of mules and asses increased by a factor of four.

Methodology

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics,

account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were estimated using the IPCC Tier 1 approach, as suggested by the *2006 IPCC Guidelines* (see the Planned Improvements section).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics. For the current Inventory, CEFM results for 1990 through 2017 were carried over from the 1990 to 2017 Inventory (i.e., 2019 Inventory submission) to focus resources on CEFM improvements, and a simplified approach was used to estimate 2018 and 2019 enteric emissions from cattle.

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation. In addition, variables and the resulting emissions are also available at the state level in Annex 3.10.

1990 to 2017 Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle

  - Calves
  - Heifer Replacements
  - Cows

- Beef Cattle

  - Calves
  - Heifer Replacements
  - Heifer and Steer Stockers
  - Animals in Feedlots (Heifers and Steer)
  - Cows
  - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2016).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999

through 2003, 2004 through 2006, 2007, and 2008 onward.[4] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5 and 6 month old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.10.

2018 and 2019 Inventory Methodology for Cattle

As noted above, a simplified approach for cattle enteric emissions was used in lieu of the CEFM for 2018 and 2019 to focus resources on CEFM improvements. First, 2018 and 2019 populations for each of the CEFM cattle sub-populations were estimated, then these populations were multiplied by the corresponding implied emission factors developed from the CEFM for the 1990 to 2017 Inventory year. Dairy cow, beef cow, and bull populations for 2019 were based on data directly from the USDA-NASS *QuickStats* database (USDA 2020, USDA 2019). Because the remaining CEFM cattle sub-population categories do not correspond exactly to the remaining *QuickStats* cattle categories, 2018 and 2019 populations for these categories were estimated by extrapolating the 2017 populations based on percent changes from 2017 to 2018 and 2018 to 2019 in similar *QuickStats* categories, consistent with Volume 1, Chapter 5 of the *2006 IPCC Guidelines* on time-series consistency. Table 5-5 lists the *QuickStats* categories used to estimate the percent change in population for each of the CEFM categories.

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[4] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

Table 5-5: Cattle Sub-Population Categories for 2018 Population Estimates

CEFM Cattle Category	USDA-NASS *QuickStats* Cattle Category
Dairy Calves	Cattle, Calves
Dairy Cows	Cattle, Cows, Milk
Dairy Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Dairy Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Milk Replacement
Bulls	Cattle, Bulls, GE 500 lbs
Beef Calves	Cattle, Calves
Beef Cows	Cattle, Cows, Beef
Beef Replacements 7-11 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Beef Replacements 12-23 months	Cattle, Heifers, GE 500 lbs, Beef Replacement
Steer Stockers	Cattle, Steers, GE 500 lbs
Heifer Stockers	Cattle, Heifers, GE 500 lbs, (Excl. Replacement)
Steer Feedlot	Cattle, On Feed
Heifer Feedlot	Cattle, On Feed

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2019. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2019 for sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA-NASS (USDA 2016). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2016); the remaining years between 1990 and 2019 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, and 2012 (USDA 2016) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison, the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC). While there are plans to update the uncertainty to reflect recent methodological updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2019 emission estimates in this Inventory.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the

three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the previous uncertainty analysis because the Food and Agricultural Organization of the United Nations (FAO) population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are now from the same USDA source as the other animal types, and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-6. Based on this analysis, enteric fermentation CH_4 emissions in 2019 were estimated to be between 158.9 and 210.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2019 emission estimate of 178.6 MMT CO_2 Eq.

Table 5-6: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	178.6	158.9	210.7	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2019 estimates.

[c] The overall uncertainty calculated in 2003, and applied to the 2019 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Category-specific or Tier 2 QA procedures included independent review of emission estimate methodologies from previous inventories.

Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current Inventory now utilizes the transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories. As noted in the Methodology discussion above, a simplified approach for cattle enteric emissions was used in lieu of the CEFM for 2018 and 2019.

Recalculations Discussion

For sheep and goats, default national emission factors were updated to reflect revisions made in the *2019 IPCC Refinement to the 2006 IPCC Guidelines* and improve the accuracy of emissions. These revised emission factors were applied to the entire time series and resulted in between 5 to 12 kt and 9 to 12 kt higher emissions for sheep and goat livestock categories, respectively.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. EPA conducts the following list of regular annual assessments of data availability when updating the estimates to extend time series each year:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;

- Updating input variables that are from older data sources, such as beef births by month, beef and dairy annual calving rates, and beef cow lactation rates;

- Investigating the availability of data for dairy births by month, to replace the current assumption that births are evenly distributed throughout the year;

- Updating the diet data to incorporate monthly or annual milk fat data in place of the fixed IPCC default value of 4 percent milk fat. EPA has investigated the availability of data across the time series and plans to incorporate annual U.S. milk fat values into the CEFM calculations in the next (i.e., 1990 to 2020) Inventory, as opposed to using a default 4 percent milk fat across the entire time series;

- Investigating the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals;

- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;

- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant;

- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States.

Depending upon the outcome of ongoing investigations, future improvement efforts for enteric fermentation could include some of the following options which are additional to the regular updates, and may or may have implications for regular updates once addressed:

- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses); efforts to move to Tier 2 will consider the emissions significance of livestock types;

- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;

- Comparison of the current CEFM processing of animal population data to estimates developed using annual average populations to determine if the model could be simplified to use annual population data;

- Comparison of the current CEFM with other models that estimate enteric fermentation emissions for quality assurance and verification;

- Investigation of recent research implications suggesting that certain parameters in enteric models may be simplified without significantly diminishing model accuracy;

- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated. EPA plans to perform this uncertainty analysis following the completed updates to the CEFM; and

- Analysis and integration of a more representative spatial distribution of animal populations by state, particularly for poultry animal populations.

EPA received comments during recent Public Review periods of the Inventory regarding the CEFM model and data and assumptions used to calculate enteric fermentation cattle emissions. Many of the comments received are consistent with potential planned improvement options listed above. EPA is continuously investigating these recommendations and potential improvements and working with USDA and other experts to utilize the best available data and methods for estimating emissions. Many of these improvements are major updates and may take multiple years to implement in full. In addition, EPA received comments during the Public Review period of the current (1990 through 2019) and previous (1990 through 2018) Inventory regarding the use of alternate metrics for weighting non-CO_2 emissions such as methane that differ from those required in reporting under the UNFCCC to facilitate comparability as described in Box 5-1.

5.2 Manure Management (CRF Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions.[5] Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO_2 and little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and animal type (particularly the different animal digestive systems), also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, N_2O emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the N in livestock dung

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[5] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

and urine.[6] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure into the groundwater below, into riparian zones receiving drain or runoff water, or into the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where organic N is mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a byproduct) (nitrification). Next, the manure must be handled anaerobically where the nitrate is then denitrified to N_2O and N_2 (denitrification). NO_x can also be produced during denitrification (Groffman et al. 2000; Robertson and Groffman 2015). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS).

Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2019 were 62.4 MMT CO_2 Eq. (2,495 kt); in 1990, emissions were 37.1 MMT CO_2 Eq. (1,485 kt). This represents a 68 percent increase in emissions from 1990. Emissions increased on average by 0.8 MMT CO_2 Eq. (2 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 49 and 117 percent, respectively. From 2018 to 2019, there was a 1 percent increase in total CH_4 emissions from manure management, due to an increase in animal populations.

Although a large quantity of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have decreased since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both

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[6] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector.

the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007, 2012, and 2017 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2019d).

In 2019, total N_2O emissions from manure management were estimated to be 19.6 MMT CO_2 Eq. (66 kt); in 1990, emissions were 14.0 MMT CO_2 Eq. (47 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have increased since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 40 percent increase from 1990 to 2019 and a 0.9 percent increase from 2018 through 2019. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted as dry manure handling systems have greater aerobic conditions that promote N_2O emissions.

Table 5-7 and Table 5-8 provide estimates of CH_4 and N_2O emissions from manure management by animal category.[7]

Table 5-7: CH₄ and N₂O Emissions from Manure Management (MMT CO₂ Eq.)

Gas/Animal Type	1990	2005	2015	2016	2017	2018	2019
CH₄[a]	**37.1**	**51.6**	**57.9**	**59.6**	**59.9**	**61.7**	**62.4**
Dairy Cattle	14.7	24.3	30.8	31.5	31.8	32.3	32.0
Swine	15.5	20.3	20.2	21.1	21.0	22.2	23.1
Poultry	3.3	3.2	3.4	3.4	3.4	3.5	3.6
Beef Cattle	3.1	3.3	3.1	3.3	3.4	3.4	3.4
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O[b]	**14.0**	**16.4**	**17.5**	**18.1**	**18.7**	**19.4**	**19.6**
Beef Cattle	5.9	7.2	7.7	8.1	8.6	9.2	9.4
Dairy Cattle	5.3	5.5	6.0	6.1	6.1	6.1	6.1
Swine	1.2	1.6	1.8	1.9	2.0	2.0	2.1
Poultry	1.4	1.6	1.6	1.6	1.6	1.7	1.7
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Total	**51.1**	**67.9**	**75.4**	**77.7**	**78.5**	**81.1**	**82.0**

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the Agricultural Soils Management sector. Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

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[7] Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

Table 5-8: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2015	2016	2017	2018	2019
CH_4[a]	**1,485**	**2,062**	**2,316**	**2,385**	**2,395**	**2,467**	**2,495**
Dairy Cattle	589	970	1,233	1,259	1,270	1,292	1,281
Swine	622	812	808	846	840	888	924
Poultry	131	129	136	136	137	141	142
Beef Cattle	126	133	126	132	136	135	136
Horses	9	12	8	8	7	7	7
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**47**	**55**	**59**	**61**	**63**	**65**	**66**
Beef Cattle	20	24	26	27	29	31	31
Dairy Cattle	18	18	20	20	20	21	20
Swine	4	5	6	6	7	7	7
Poultry	5	5	5	5	5	6	6
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the Agricultural Soils Management sector. Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM previously described for Enteric Fermentation. This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management. For the current Inventory, time-series results were carried over from the 1990 to 2018 Inventory (i.e., 2020 submission) and a simplified approach was used to estimate manure management emissions for 2019.

See Annex 3.11 for more detailed information on the methodology (including detailed formulas and emission factors), data used to calculate CH_4 and N_2O emissions, and emission results (including input variables and results at the state-level) from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2018:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- Volatile solids (VS) production rate (by animal type and state or United States);
- Methane producing potential (B_0) of the volatile solids (by animal type); and

- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2018 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017; and American bison population for 2002, 2007, 2012, and 2017 were obtained from the *Census of Agriculture* (USDA 2019d). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).

- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM used for cattle, see Annex 3.10.

- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016c) and EPA (ERG 2000a; EPA 2002a and 2002b; ERG 2018, ERG 2019). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.

- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.

- B_0 was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).

- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.

- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information available in the AgSTAR project database (EPA 2019). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).

- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per

day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) were multiplied by the B_0 (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions. See details in Step 5 of Annex 3.11.

The following approach was used in the calculation of manure management CH_4 emissions for 2019:

- EPA obtained 2019 national-level animal population data: Sheep, poultry, and swine data were downloaded from USDA-NASS Quickstats (USDA 2020). Cattle populations were obtained from the CEFM (see NIR Section 5.1 and Annex 3.10). Data for goats, horses, bison, mules, and asses were extrapolated based on the 2009 through 2018 population values to reflect recent trends in animal populations.

- EPA multiplied the national populations by the animal-specific 2018 implied emission factors[8] for CH_4 to calculate national-level 2019 CH_4 emissions estimates by animal type. These methods were utilized in order to maintain time-series consistency as referenced in Volume 1, Chapter 5 of the *2006 IPCC Guidelines*.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2018:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex were assumed to be the same as NOF bulls.[9]

- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).

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[8] An implied emission factor is defined as emissions divided by the relevant measure of activity; the implied emission factor is equal to emissions per activity data unit. For source/sink categories that are composed of several subcategories, the emissions and activity data are summed up across all subcategories. Hence, the implied emission factors are generally not equivalent to the emission factors used to calculate emission estimates, but are average values that could be used, with caution, in data comparisons (UNFCCC 2017).

[9] Nex of American bison on grazing lands are accounted for and discussed in the Agricultural Soil Management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the Manure Management source category, there are no N_2O emissions from American bison included in the Manure Management source category.

- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year). See details in Step 6 of Annex 3.11.

Indirect N_2O emissions from volatilization (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{gas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions. See details in Step 6 of Annex 3.11.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2018.

The following approach was used in the calculation of manure management N_2O emissions for 2019:

- EPA obtained 2019 national-level animal population data: Sheep, poultry, and swine data were downloaded from USDA-NASS Quickstats (USDA 2020). Cattle populations were obtained from the CEFM, see Section 5.1 and Annex 3.10 (Enteric Fermentation). Data for goats, horses, bison, mules, and asses were extrapolated based on the 2009 through 2018 population values to reflect recent trends in animal populations.

- The national populations were multiplied by the animal-specific 2018 implied emission factors for N_2O (which combines both direct and indirect N_2O) to calculate national-level 2019 N_2O emissions estimates by animal type. These methods were utilized in order to maintain time-series consistency as referenced in Volume 1, Chapter 5 of the *2006 IPCC Guidelines*.

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. While there are plans to update the uncertainty to reflect recent manure management updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2019 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-9. Manure management CH_4 emissions in 2019 were estimated to be between 51.1 and 74.8 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2019 emission estimate of 62.4 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 16.5 and 24.3 MMT CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2019 emission estimate of 19.6 MMT CO_2 Eq.).

Table 5-9: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	62.4	51.1	74.8	-18%	+20%
Manure Management	N_2O	19.6	16.5	24.3	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. In addition, manure N data were checked by comparing state-level data with bottom-up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted and the sum of county estimates for the full time series.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_0, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2018 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values.[10] Table 5-10 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry

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[10] CH_4 implied emission factors were not calculated for 2019 due to the simplified emissions estimation approach used to estimate emissions for that year; therefore, those values are consistent with 2018.

trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions.

Table 5-10: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH₄ from Manure Management (kg/head/year)

Animal Type	IPCC Default CH₄ Emission Factors (kg/head/year)[a]	Implied CH₄ Emission Factors (kg/head/year)						
		1990	2005	2015	2016	2017	2018	2019
Dairy Cattle	48-112	30.2	54.5	65.6	66.8	67.2	67.9	67.9
Beef Cattle	1-2	1.5	1.6	1.7	1.7	1.7	1.6	1.6
Swine	10-45	11.5	13.3	11.8	12.1	11.7	12.0	12.0
Sheep	0.19-0.37	0.6	0.6	0.5	0.5	0.5	0.5	0.5
Goats	0.13-0.26	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Poultry	0.02-1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	1.56-3.13	4.3	3.1	2.6	2.6	2.6	2.6	2.6
American Bison	NA	1.8	2.0	2.1	2.1	2.1	2.1	2.1
Mules and Asses	0.76-1.14	0.9	1.0	1.0	1.0	1.0	1.0	1.0

Note: CH₄ implied emission factors were not calculated for 2019 due to the simplified emissions estimation approach used to estimate emissions for that year. 2018 values were used for 2019.

NA (Not Applicable)

[a] Ranges reflect *2006 IPCC Guidelines* (Volume 4, Table 10.14) default emission factors for North America across different climate zones.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. Inventory implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. Inventory values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

No recalculations were performed for the 1990 to 2018 estimates. The 2019 estimates were developed using a simplified approach, as discussed in the Methodology section.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. EPA conducts the following list of regular annual assessments of data availability when updating the estimates to extend time series each year. EPA is actively pursuing the following updates but notes that implementation may be based on available resources and data availability:

- Continuing to investigate new sources of WMS data. EPA is working with the USDA Natural Resources Conservation Service to collect data for potential improvements to the Inventory. EPA expects the next WMS systems to be updated for the next (i.e., 1990 to 2020) Inventory submission include poultry and beef cattle.

- Updating the B_0 data used in the Inventory, as data become available. EPA is conducting outreach with counterparts from USDA as to available data and research on B_0.

- Revising the methodology for population distribution to states where USDA population data are withheld due to disclosure concerns. These updates will be made in collaboration with the EPA National Emissions Inventory staff to improve consistency across U.S. inventories. EPA plans to incorporate these updates into the next (i.e., 1990 to 2020) Inventory submission.

IPCC's *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* provides updated emission factors that EPA plans to review and implement for manure management (IPCC 2019). EPA maintains from previous reports that many of the improvements identified below are major updates and may take multiple years to fully implement. Potential improvements (long-term improvements) for future Inventory years include:

- Revising the anaerobic digestion estimates to estimate CH_4 emissions *reductions* due to the use of anaerobic digesters (the Inventory currently estimates only emissions from anaerobic digestion systems).

- Investigating improved emissions estimate methodologies for swine pit systems with less than one month of storage (the recently updated swine WMS data included this WMS category).

- Comparing CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the Inventory.

- Comparing manure management emission estimates with on-farm measurement data to identify opportunities for improved estimates.

- Comparing VS and Nex data to literature data to identify opportunities for improved estimates.

- Improving collaboration with the Enteric Fermentation source category estimates. For future inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and they depend on each other's outputs to properly calculate emissions.

- Revising the uncertainty analysis to address changes that have been implemented to the CH_4 and N_2O estimates. EPA plans to line up the timing of performing the updated Manure Management uncertainty analysis with the uncertainty analysis for Enteric Fermentation.

5.3 Rice Cultivation (CRF Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013) that create anaerobic conditions leading to CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions in rice cultivation, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practice in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have fewer living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the

amount of root exudates[11] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b). Fertilization practices also influence CH_4 emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linquist et al. 2012), which can reduce CH_4 emissions. Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature regulates the activity of methanogenic bacteria, which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in thirteen states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is grown in the Southeastern region of the country. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

A combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, while a surrogate data method has been applied to estimate national emissions for 2016 to 2019 in this Inventory due to lack of data in the later years of the time series. National emission estimates based on surrogate data will be recalculated in a future Inventory with the Tier 1 and 3 methods as data becomes available.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-11, Table 5-12, and Figure 5-3). Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri and Texas. In 2019, CH_4 emissions from rice cultivation were 15.1 MMT CO_2 Eq. (602 kt). Annual emissions fluctuate between 1990 and 2019, which is largely due to differences in the amount of rice harvested areas over time, which has been decreasing over the past two decades. Consequently, emissions in 2019 are six percent lower than emissions in 1990.

Table 5-11: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990		2005		2015	2016	2017	2018	2019
Arkansas	5.4		7.9		6.4	NE	NE	NE	NE
California	3.3		3.4		4.1	NE	NE	NE	NE
Florida	+		+		+	NE	NE	NE	NE
Illinois	+		+		+	NE	NE	NE	NE
Kentucky	+		+		+	NE	NE	NE	NE
Louisiana	2.6		2.8		2.6	NE	NE	NE	NE
Minnesota	+		0.1		+	NE	NE	NE	NE
Mississippi	1.1		1.4		1.0	NE	NE	NE	NE
Missouri	0.6		1.1		0.7	NE	NE	NE	NE
New York	+		+		+	NE	NE	NE	NE
South Carolina	+		+		+	NE	NE	NE	NE
Tennessee	+		+		+	NE	NE	NE	NE
Texas	3.0		1.3		1.4	NE	NE	NE	NE
Total	**16.0**		**18.0**		**16.2**	**15.8**	**14.9**	**15.6**	**15.1**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.

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[11] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb and use to stimulate more production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

NE (Not Estimated). State-level emissions are not estimated for 2016 through 2019 in this Inventory because data are unavailable. A surrogate data method is used to estimate emissions for these years and are produced only at the national scale.

Table 5-12: CH₄ Emissions from Rice Cultivation (kt)

State	1990		2005		2015	2016	2017	2018	2019
Arkansas	216		315		256	NE	NE	NE	NE
California	131		134		166	NE	NE	NE	NE
Florida	+		1		+	NE	NE	NE	NE
Illinois	+		+		+	NE	NE	NE	NE
Kentucky	+		+		+	NE	NE	NE	NE
Louisiana	103		113		103	NE	NE	NE	NE
Minnesota	1		2		+	NE	NE	NE	NE
Mississippi	45		55		40	NE	NE	NE	NE
Missouri	22		45		26	NE	NE	NE	NE
New York	+		+		+	NE	NE	NE	NE
South Carolina	+		+		+	NE	NE	NE	NE
Tennessee	+		+		+	NE	NE	NE	NE
Texas	122		54		57	NE	NE	NE	NE
Total	**640**		**720**		**648**	**631**	**596**	**623**	**602**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2016 through 2019 in this Inventory because data are unavailable. A surrogate data method is used to estimate emissions for these years and are produced only at the national scale.

Figure 5-3: Annual CH₄ Emissions from Rice Cultivation, 2015
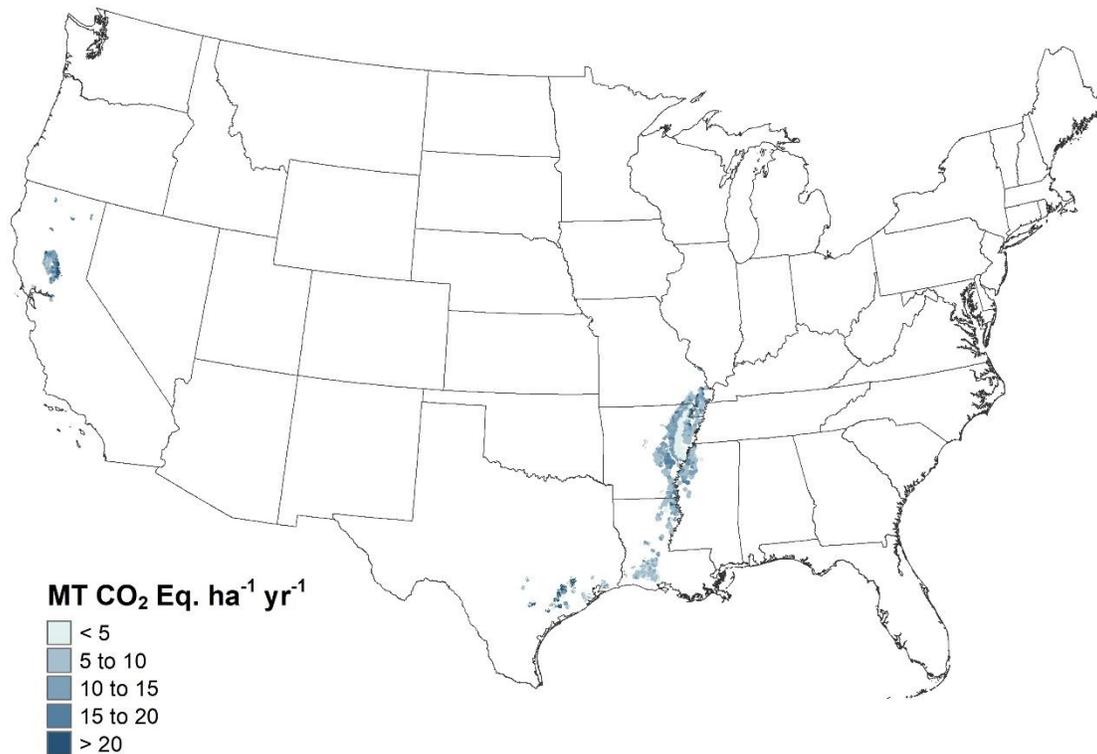
MT CO₂ Eq. ha⁻¹ yr⁻¹
- □ < 5
- □ 5 to 10
- ■ 10 to 15
- ■ 15 to 20
- ■ > 20

Note: Only national-scale emissions are estimated for 2016 through 2019 in this Inventory using the surrogate data method

described in the Methodology section; therefore, the fine-scale emission patterns in this map are based on the estimates for 2015.

Methodology

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013), and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil C stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010), and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission rate represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust the base emission rate for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping, ratooning, etc.). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[12]

Rice cultivation areas are based on cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2018). The NRI is a statistically-based sample of all non-federal land, and includes 489,178 survey locations in agricultural land for the conterminous United States and Hawaii of which 1,960 include one or more years of rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 1,655 of the NRI survey locations, and the remaining 305 survey locations are estimated with the Tier 1 method. Each NRI survey location is associated with an "expansion factor" that allows scaling of CH_4 emission to the entire land base with rice cultivation (i.e., each expansion factor represents the amount of area with the same land-use/management history as the survey location). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in 4 out of 5 years for each 5-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data currently available through 2015 (USDA-NRCS 2018). The current Inventory only uses NRI data through 2015 because newer data are not available, but will be incorporated when additional years of data are released by USDA-NRCS. The harvested rice areas in each state are presented in Table 5-13.

Table 5-13: Rice Area Harvested (1,000 Hectares)

State/Crop	1990		2005		2015	2016	2017	2018	2019
Arkansas	600		784		679	NE	NE	NE	NE
California	249		236		280	NE	NE	NE	NE

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[12] See <http://www.nrel.colostate.edu/projects/ALUsoftware/>.

State							
Florida	0	4	0	NE	NE	NE	NE
Illinois	0	0	0	NE	NE	NE	NE
Kentucky	0	0	0	NE	NE	NE	NE
Louisiana	381	402	368	NE	NE	NE	NE
Minnesota	4	9	1	NE	NE	NE	NE
Mississippi	123	138	98	NE	NE	NE	NE
Missouri	48	94	62	NE	NE	NE	NE
New York	1	0	0	NE	NE	NE	NE
South Carolina	0	0	0	NE	NE	NE	NE
Tennessee	0	1	0	NE	NE	NE	NE
Texas	302	118	131	NE	NE	NE	NE
Total	**1,707**	**1,788**	**1,619**	**NE**	**NE**	**NE**	**NE**

Note: Totals may not sum due to independent rounding.

NE (Not Estimated). State-level area data are not available for 2016 through 2019 but will be
  added in a future Inventory with release of new NRI survey data.

The Southeastern states have sufficient growing periods for a ratoon crop in some years (Table 5-14). For example, the growing season length is occasionally sufficient for ratoon crops to be grown on about 1 percent of the rice fields in Arkansas. No data are available about ratoon crops in Missouri or Mississippi, and the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California.

Table 5-14: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2015
Arkansas[a]	1%
California	0%
Florida[b]	49%
Louisiana[c]	32%
Mississippi[a]	1%
Missouri[a]	1%
Texas[d]	45%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014). Estimates of ratooning for Missouri and Mississippi are based on the data from Arkansas.

[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014).

[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).

[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DayCent simulations and the Tier 1 method. Variation in flooding can be incorporated in future Inventories if water management data are collected.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during winter flooding. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson

et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the Inventory time series.

A surrogate data method is used to estimate emissions from 2016 to 2019 associated with the rice CH_4 emissions for Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2015, which were derived using the Tier 1 and 3 methods (Brockwell and Davis 2016). Surrogate data are based on rice commodity statistics from USDA-NASS.[13] See Box 5-2 for more information about the surrogate data method.

Box 5-2: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from Rice Cultivation because there are gaps in activity data at the end of the time series. This is mainly due to the fact that the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2015 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., CH_4 emissions), $X\beta$ is the surrogate data that is used to predict the missing emissions data, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2015 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2016 to 2019.

A critical issue in using splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2015).

Uncertainty and Time-Series Consistency

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. A Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods. For 2016 to 2019, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method (See Box 5-2 for information about propagating uncertainty with the surrogate data method). The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12.

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[13] See <https://quickstats.nass.usda.gov/>.

Rice cultivation CH_4 emissions in 2019 were estimated to be between 3.8 and 37.5 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 75 percent below to 149 percent above the 2019 emission estimate of 15.1 MMT CO_2 Eq. (see Table 5-15).

Table 5-15: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
				(MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	12.5	1.4	23.7	-89%	+89%
Rice Cultivation	Tier 1	CH_4	2.5	1.3	3.7	-48%	+48%
Rice Cultivation	**Total**	**CH_4**	**15.1**	**3.8**	**37.5**	**-75%**	**+149%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. One error was found in the Tier-3 linear regression with ARMA surrogate data method and corrected. For each Monte Carlo iteration, total CH_4 emissions data were transformed using a constant scaler to meet the model requirement, however during the back-transformation only one constant was used for all Monte Carlo iteration. This results in a bias model prediction and lower uncertainty in the previous year's inventory. The estimates were corrected by updating the code and emissions were re-estimated for the years 2016 to 2019.

Model results are compared to field measurements to verify if results adequately represent CH_4 emissions. The comparisons included over 17 long-term experiments, representing about 238 combinations of management treatments across all the sites. A statistical relationship was developed to assess uncertainties in the model structure, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Emissions data from 2016 to 2018 were corrected based on an error in the data splicing method (see QA/QC and Verification section). This change resulted in an average increase in CH_4 emissions of 2.2 MMT CO_2 Eq., or 2.3 percent, from 2016 to 2018 relative to the previous Inventory.

Planned Improvements

A key planned improvement for rice cultivation is to fill several gaps in the management activity including compiling new data on water management, organic amendments and ratooning practices in rice cultivation systems. This improvement is expected to be completed for the next Inventory, but may be prioritized considering overall improvements to make best use of available resources.

5.4 Agricultural Soil Management (CRF Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[14] Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[15] Several agricultural activities increase mineral N availability in soils that lead to direct N_2O emissions at the site of a management activity (see Figure 5-4) (Mosier et al. 1998). These activities include synthetic N fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (N-fixing legumes and non-legume crops and forages); and drainage of organic soils[16] (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence N mineralization from soil organic matter and levels of asymbiotic N fixation. Indirect emissions of N_2O occur when N is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[17] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1 Representation of the U.S. Land Base). Nitrous oxide emissions from Forest Land and Settlements soils are found in Sections 6.2 and 6.10, respectively.

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[14] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

[15] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[16] Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[17] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases in the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x. In addition, hydrological processes lead to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems, e.g., wetlands, rivers, streams and lakes. Note: N_2O emissions are not estimated for aquatic systems associated with N inputs from terrestrial systems in order to avoid double-counting.

Figure 5-4: Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management

Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management
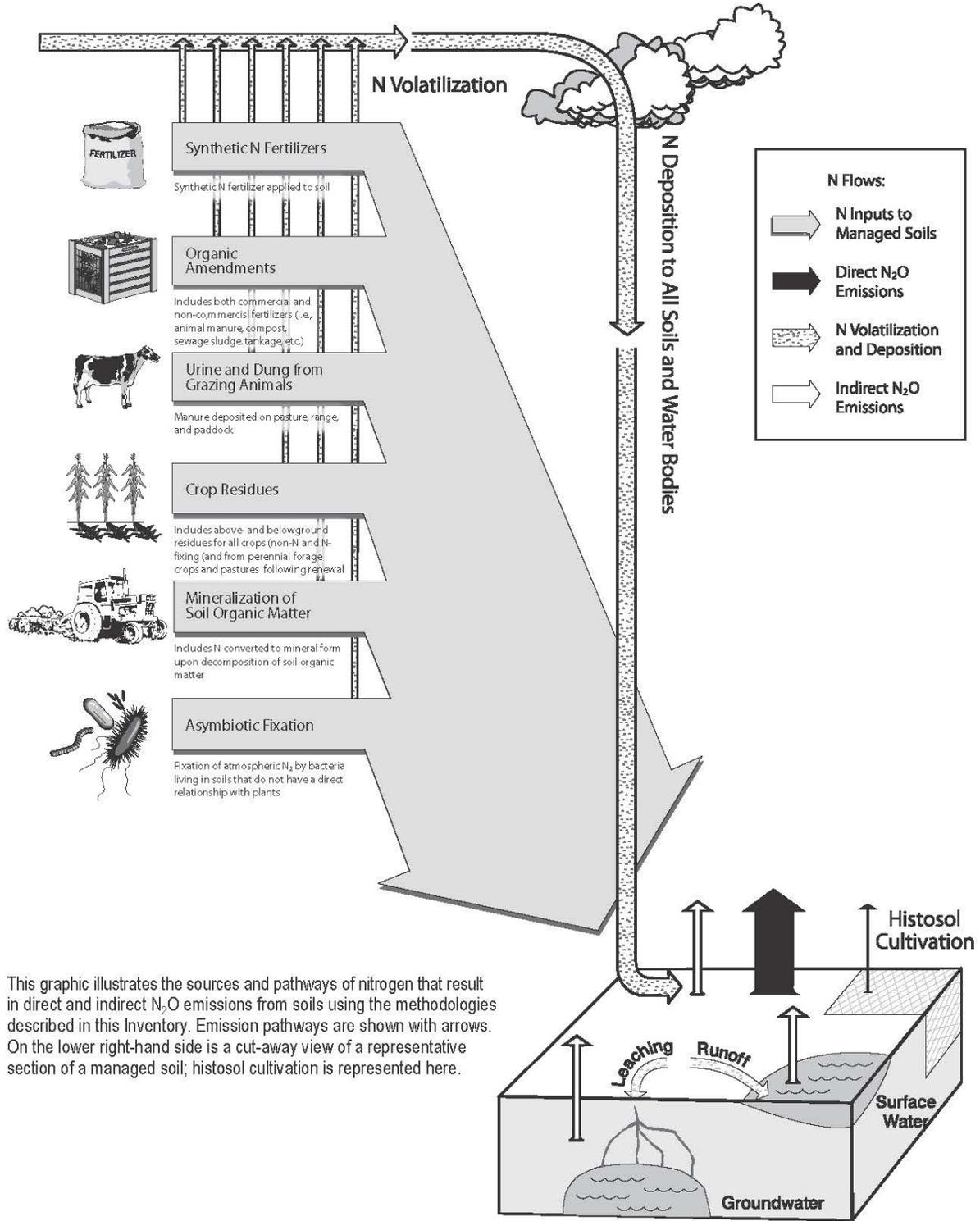
Agricultural soils produce the majority of N$_2$O emissions in the United States. Estimated emissions in 2019 are 344.6 MMT CO$_2$ Eq. (1,156 kt) (see Table 5-16 and Table 5-17). Annual N$_2$O emissions from agricultural soils are 9 percent greater in the 2019 compared to 1990, but emissions fluctuated between 1990 and 2019 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2019, cropland accounted for 68 percent of total direct emissions on average, while grassland accounted for 32 percent. On average, 79 percent of indirect emissions are from croplands and 21 percent from grasslands. Estimated direct and indirect N$_2$O emissions by sub-source category are shown in Table 5-18 and Table 5-19.

Table 5-16: N$_2$O Emissions from Agricultural Soils (MMT CO$_2$ Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Direct	**272.5**		**272.6**		**295.0**	**281.4**	**280.3**	**285.9**	**290.4**
Cropland	185.9		183.7		199.5	190.8	190.4	195.1	196.4
Grassland	86.6		88.8		95.4	90.6	89.9	90.9	94.0
Indirect	**43.4**		**40.8**		**53.5**	**48.7**	**47.3**	**52.3**	**54.2**
Cropland	34.2		31.6		42.7	38.8	37.4	42.3	43.8
Grassland	9.2		9.2		10.8	9.9	9.8	10.0	10.4
Total	**315.9**		**313.4**		**348.5**	**330.1**	**327.6**	**338.2**	**344.6**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-17: N$_2$O Emissions from Agricultural Soils (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Direct	**914.5**		**914.7**		**989.9**	**944.3**	**940.6**	**959.5**	**974.5**
Cropland	623.8		616.6		669.6	640.3	639.0	654.5	659.1
Grassland	290.7		298.1		320.2	304.1	301.6	305.0	315.5
Indirect	**145.6**		**137.0**		**179.6**	**163.4**	**158.6**	**175.5**	**181.9**
Cropland	114.8		106.1		143.2	130.3	125.5	142.0	147.1
Grassland	30.7		30.9		36.4	33.1	33.0	33.4	34.8
Total	**1,060.1**		**1,051.6**		**1,169.4**	**1,107.7**	**1,099.2**	**1,135.0**	**1,156.4**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-18: Direct N$_2$O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO$_2$ Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
Cropland	**185.8**		**183.7**		**199.5**	**190.8**	**190.4**	**195.0**	**196.4**
Mineral Soils	**182.1**		**180.0**		**196.1**	**187.4**	**187.0**	**191.6**	**193.0**
Synthetic Fertilizer	63.1		64.0		64.8	68.8	68.5	70.1	70.4
Organic Amendment[a]	12.6		13.0		13.4	14.5	14.3	14.3	14.2
Residue N[b]	39.3		39.6		39.0	40.1	40.1	41.2	41.6
Mineralization and Asymbiotic Fixation	67.1		63.3		78.9	64.0	64.1	66.1	66.8
Drained Organic Soils	**3.8**		**3.7**		**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Grassland	**86.7**		**88.9**		**95.5**	**90.6**	**89.9**	**90.9**	**94.0**
Mineral Soils	**84.2**		**86.5**		**93.0**	**88.2**	**87.4**	**88.4**	**91.6**
Synthetic Fertilizer	+		+		+	+	+	+	+
PRP Manure	14.6		13.4		12.8	12.8	12.8	12.9	13.2
Managed Manure[c]	+		+		+	+	+	+	+
Biosolids (i.e., treated Sewage Sludge)	0.2		0.5		0.6	0.6	0.6	0.6	0.7
Residue N[d]	29.7		30.8		30.4	31.5	31.2	31.6	32.8
Mineralization and Asymbiotic Fixation	39.5		41.7		49.2	43.2	42.8	43.3	44.9

Drained Organic Soils	2.5	2.4	2.5	2.5	2.5	2.5	2.5
Total	272.5	272.6	295.0	281.4	280.3	285.9	290.4

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

[d] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N.

Table 5-19: Indirect N₂O Emissions from Agricultural Soils (MMT CO₂ Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
Cropland	**34.2**	**31.6**	**42.7**	**38.8**	**37.4**	**42.3**	**43.8**
Volatilization & Atm. Deposition	6.5	7.3	8.5	8.1	7.9	8.0	7.9
Surface Leaching & Run-Off	27.7	24.4	34.2	30.7	29.5	34.4	35.9
Grassland	**9.2**	**9.2**	**10.8**	**9.9**	**9.8**	**10.0**	**10.4**
Volatilization & Atm. Deposition	3.6	3.6	3.7	3.5	3.5	3.5	3.6
Surface Leaching & Run-Off	5.6	5.6	7.2	6.4	6.3	6.4	6.8
Total	**43.4**	**40.8**	**53.5**	**48.7**	**47.3**	**52.3**	**54.2**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Figure 5-5 and Figure 5-6 show regional patterns for direct N₂O emissions. Figure 5-7 and Figure 5-8 show indirect N₂O emissions from volatilization, and Figure 5-9 and Figure 5-10 show the indirect N₂O emissions from leaching and runoff in croplands and grasslands, respectively.

Figure 5-5: Croplands, 2015 Annual Direct N$_2$O Emissions Estimated Using the Tier 3 DayCent Model
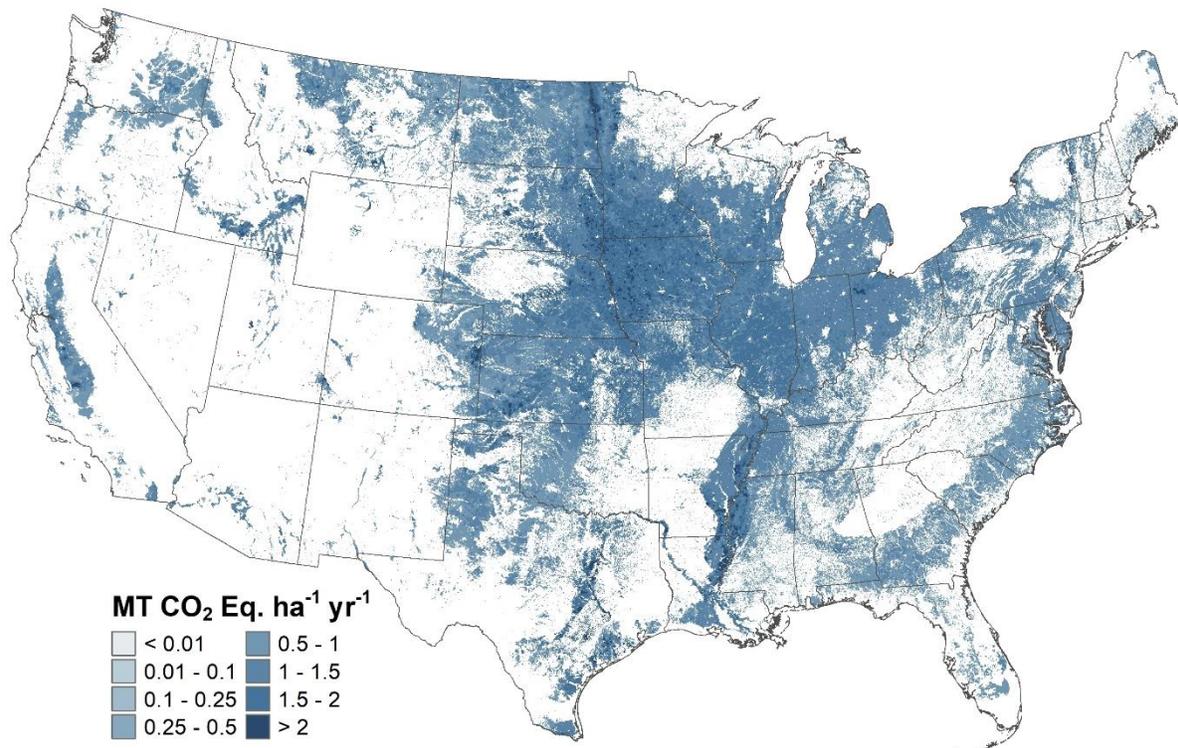
MT CO$_2$ Eq. ha^{-1} yr^{-1}

< 0.01	0.5 - 1
0.01 - 0.1	1 - 1.5
0.1 - 0.25	1.5 - 2
0.25 - 0.5	> 2

Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Direct N$_2$O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (Illinois, Iowa, Indiana, Ohio, southern Minnesota and Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (see Figure 5-5). Kansas, South Dakota and North Dakota have relatively high emissions from large areas of crop production that are found in the Great Plains region. Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado through Nebraska, Snake River Valley in Idaho and the Central Valley in California. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated, and in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are more evenly distributed throughout the United States (see Figure 5-6), but total emissions tend be highest in the Great Plains and western United States where a large proportion of the land is dominated by grasslands with cattle and sheep grazing. However, there are relatively large emissions from local areas in the Eastern United States, particularly Kentucky and Tennessee, in addition to areas in Missouri and Iowa, where there can be higher rates of Pasture/Range/Paddock (PRP) manure N additions on a relatively small amount of pasture. These areas have greater stocking rates of livestock per unit of area, compared to other regions of the United States.

Figure 5-6: Grasslands, 2015 Annual Direct N₂O Emissions Estimated Using the Tier 3 DayCent Model
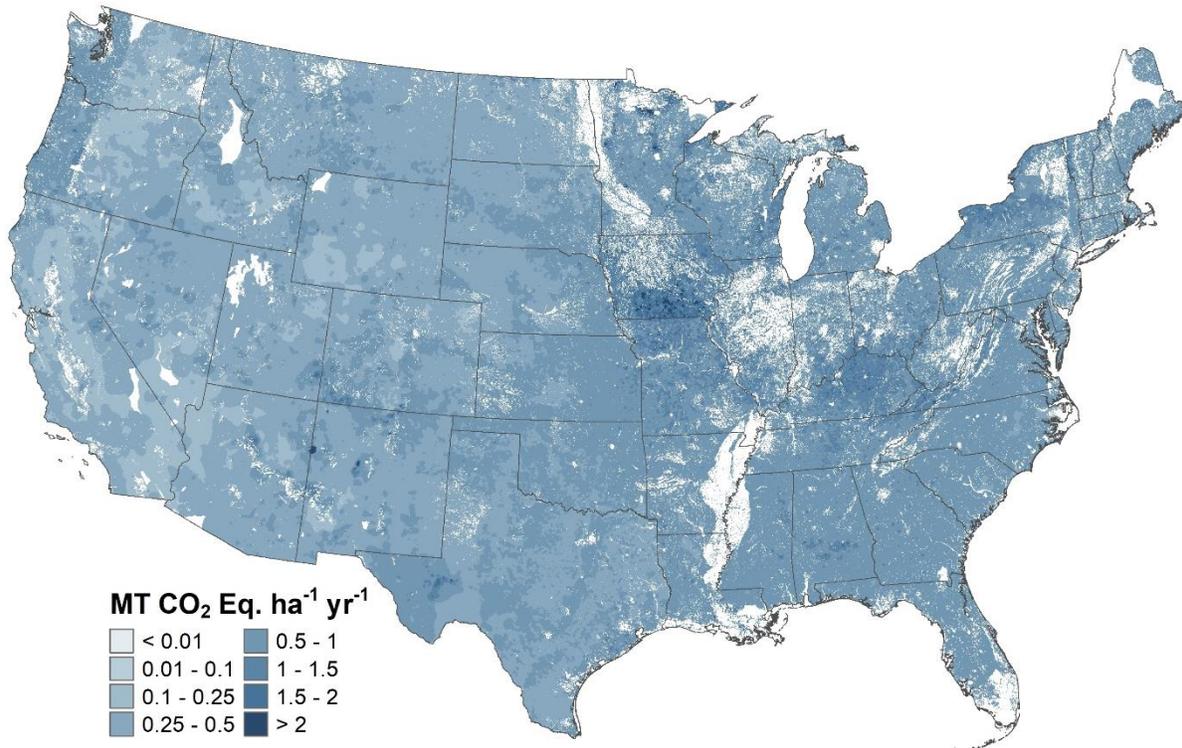
Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin and Great Plains. Indirect N_2O emissions from volatilization in grasslands are higher in the Southeastern United States, along with portions of the Mid-Atlantic and southern Iowa. The higher emissions in this region are mainly due to large additions of PRP manure N on relatively small but productive pastures that support intensive grazing, which in turn, stimulates NH_3 volatilization.

Indirect N_2O emissions from surface runoff and leaching of applied/mineralized N in croplands is highest in the Midwestern Corn Belt. There are also relatively high emissions associated with N management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states. In addition, areas of high emissions occur in portions of the Great Plains that have relatively large areas of irrigated croplands with high leaching rates of applied/mineralized N. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized N in grasslands are higher in the eastern United States and coastal Northwest region. These regions have greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Figure 5-7: Croplands, 2015 Annual Indirect N₂O Emissions from Volatilization Using the Tier 3 DayCent Model
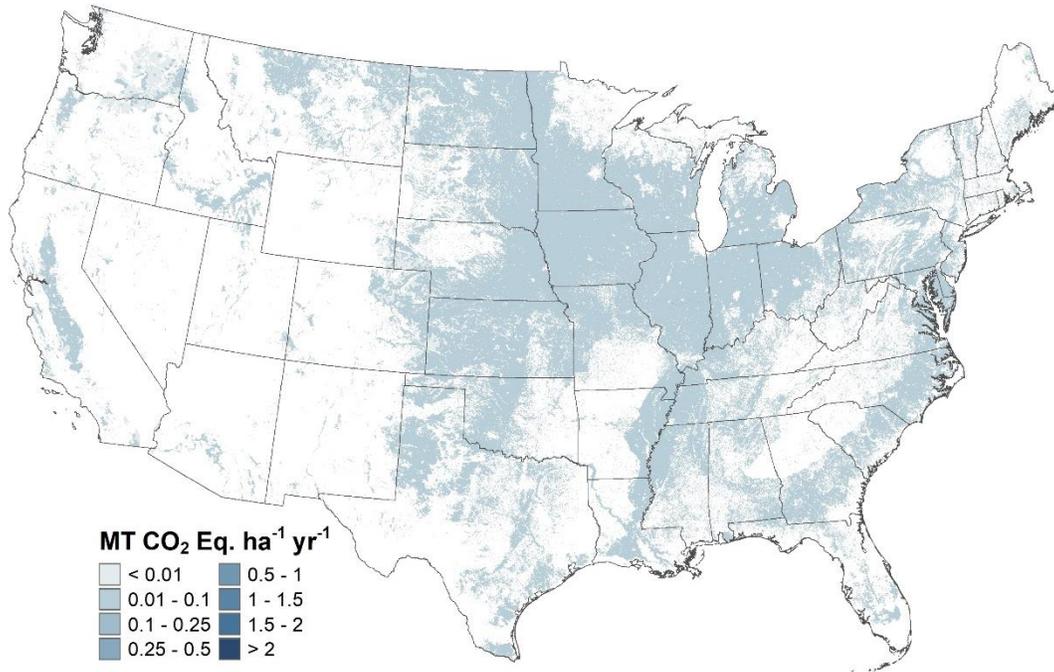
Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-8: Grasslands, 2015 Annual Indirect N₂O Emissions from Volatilization Using the Tier 3 DayCent Model
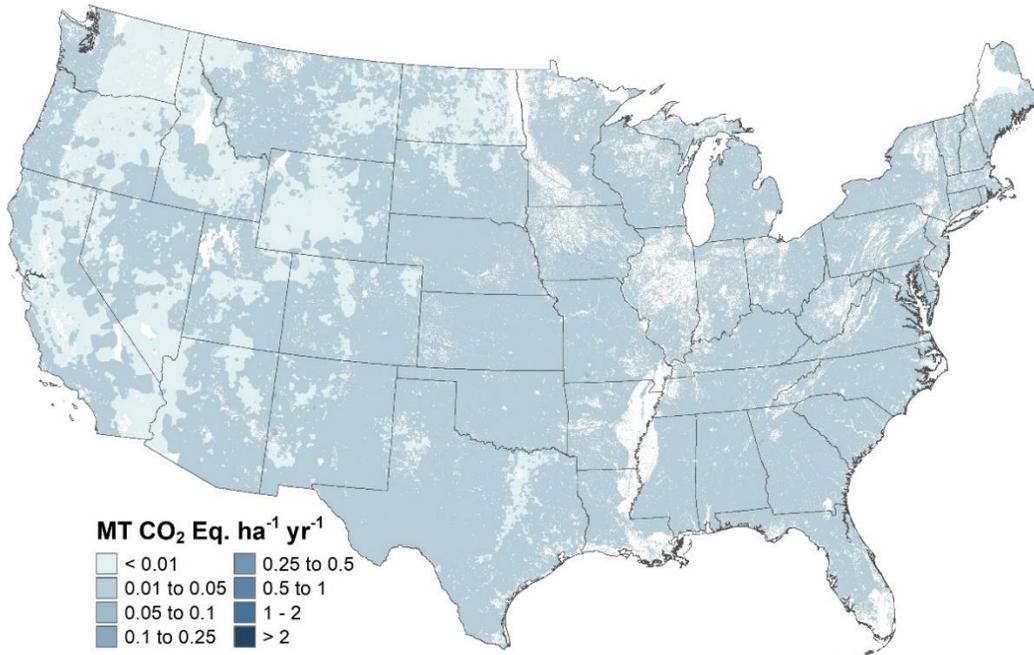
Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-9: Croplands, 2015 Annual Indirect N₂O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model
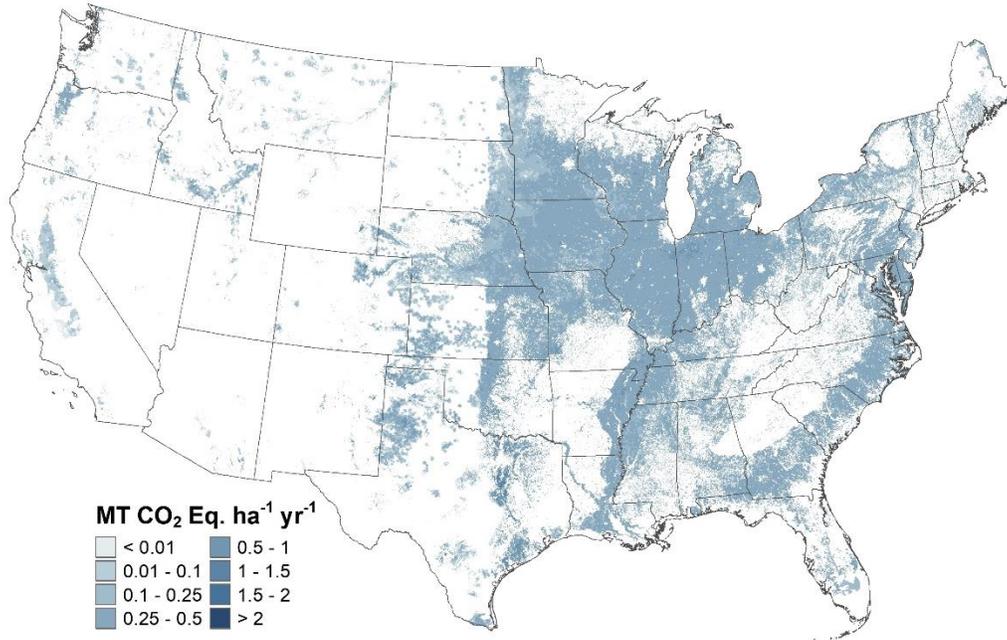
Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-10: Grasslands, 2015 Annual Indirect N₂O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model
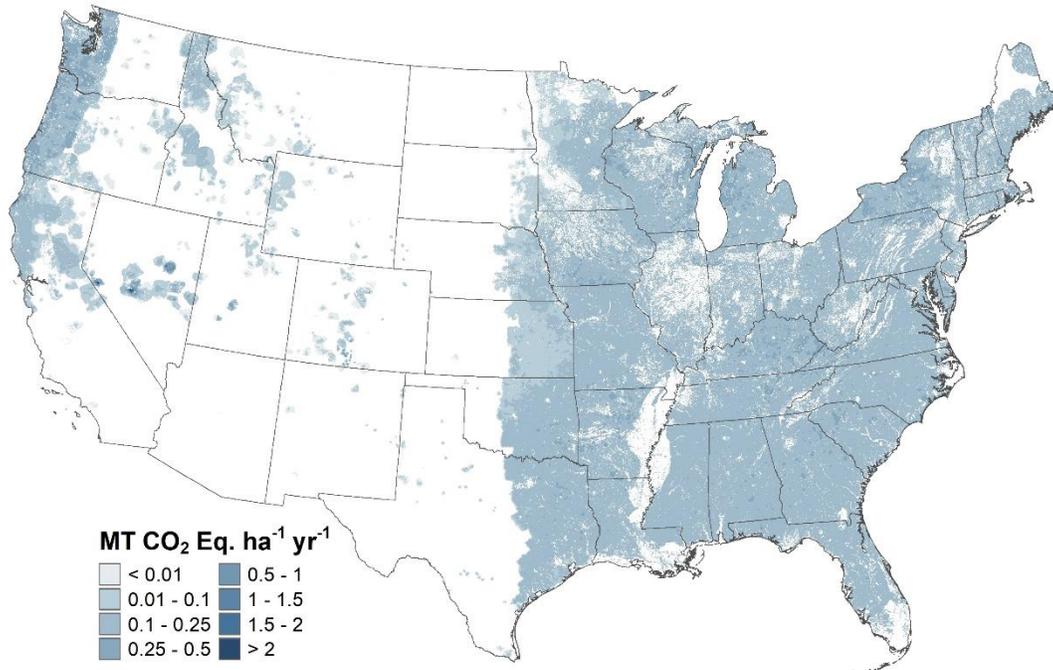
Note: Only national-scale emissions are estimated for 2016 to 2019 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from N additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., treated sewage sludge), crop residues (legume N-fixing and non-legume crops), and organic amendments; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all managed grasslands, whereby anthropogenic greenhouse gas emissions are estimated consistent with the managed land concept (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[18] and mineralization of N associated with decomposition of soil organic matter and residues. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter years in the Inventory time series (IPCC 2006; Del Grosso et al. 2010) where data are not yet available. A Tier 3 process-based model (DayCent) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-3 for further elaboration). Moreover, the Tier 3 approach addresses direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are considered between C and N cycling in soils.

The Tier 3 approach is based on the crop and land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2018a). The NRI is a statistically-based sample of all non-federal land,[19] and includes 349,464 points on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from 175,527 locations in the NRI survey across the time series, which are designated as cropland or grassland (discussed later in this section). Each survey location is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the survey location). Each NRI survey location was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, which are currently available through 2015 (USDA-NRCS 2018a).

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[18] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the N inputs and total emissions from managed lands and are included in the Tier 3 approach developed for this source.

[19] The NRI survey does include sample points on federal lands, but the program does not collect data from those sample locations.

DayCent is used to estimate N₂O emissions associated with production of alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, but is not applied to estimate N₂O emissions from other crops or rotations with other crops,[20] such as sugarcane, some vegetables, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DayCent. DayCent is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N₂O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DayCent due to limited activity data on land use histories. For areas that are not included in the DayCent simulations, Tier 1 methods are used to estimate emissions, including (1) direct emissions from N inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP N additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N₂O emissions from 2016 to 2019 at the national scale because new NRI activity data are not available for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions that are derived using the Tier 3 method. Surrogate data for these regression models includes corn and soybean yields from USDA-NASS statistics,[21] and weather data from the PRISM Climate Group (PRISM 2018). For the Tier 1 method, a linear-time series model is used to estimate emissions from 2016 to 2019 without surrogate data for most of the N sources (exceptions include biosolids, drainage of organic soils, and

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[20] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DayCent.
[21] See <https://quickstats.nass.usda.gov/>.

crop residue N). See Box 5-4 for more information about the splicing method. Emission estimates for 2016 to 2019 will be recalculated in future Inventory reports when new NRI data are available.

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Box 5-4: Surrogate Data Method

An approach to extend the time series is needed for Agricultural Soil Management because there are typically activity data gaps at the end of the time series. This is mainly because the NRI survey program, which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the modeled 1990 to 2015 emissions data, which has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil nitrous oxide), $X\beta$ for the Tier 3 method contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. The term $X\beta$ for the Tier 1 method only contains year as a predictor of emission patterns over the time series (change in emissions per year), and therefore, is a linear time series model with no surrogate data. Parameters are estimated from the emissions data for 1990 to 2015 using standard statistical techniques, and these estimates are used in the model described above to predict the missing emissions data for 2016 to 2019.

A critical issue with splicing methods is to account for the additional uncertainty introduced by predicting emissions without compiling the full inventory. Specifically, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This additional uncertainty is quantified within the model framework using a Monte Carlo approach. Consequently, the uncertainty from the original inventory data is combined with the uncertainty in the data splicing model. The approach requires estimating parameters in the data splicing models in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the draws of parameters values that are selected in each Monte Carlo iteration, and used to produce estimates with inventory data from 1990 to 2015). Therefore, the data splicing method generates emissions estimates from each surrogate data model in the Monte Carlo analysis, which are used to derive confidence intervals in the estimates for the missing emissions data from 2016 to 2019. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

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Tier 3 Approach for Mineral Cropland Soils

The DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous section) based on the crop histories in the 2015 NRI (USDA-NRCS 2018a). Crops simulated by DayCent are grown on approximately 85 percent of total cropland area in the United States. The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1[22] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2018), and

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[22] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2015. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature, and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). DayCent is used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) application of synthetic fertilizers; (2) application of livestock manure; (3) retention of crop residues in the field for N-fixing legumes and non-legume crops and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of N from decomposition of soil organic matter; and (5) asymbiotic fixation.

Management activity data from several sources supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. These data are combined with other datasets in an imputation analysis that extend the time series from 1990 to 2015. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below), b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994), and c) assign management practices from the CEAP survey to specific NRI locations using predictive mean matching methods that are adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a very large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments from 1979 to 2015, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2018). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both rates. This approach captures the relationship between mineral fertilization and manure amendment practices for U.S. croplands based directly on the observed patterns in the CEAP survey data.

To determine the trends in tillage management from 1979 to 2015, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and USDA-ERS Agriculture Resource Management Surveys (ARMS) data from 2002 to 2015 (Claasen et al. 2018). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). It is assumed that the majority of agricultural lands are managed with full tillage prior to 1985.

For cover crops, CEAP data are combined with information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

The IPCC method considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DayCent simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DayCent accounts for the influence of symbiotic N fixation, mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs.

The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double counting associated with non-CO_2 greenhouse gas

emissions from agricultural residue burning. Estimated levels of residue burning are based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Uncertainty in the emission estimates from DayCent is associated with input uncertainty due to missing management data in the NRI survey that is imputed from other sources; model uncertainty due to incomplete specification of C and N dynamics in the DayCent model parameters and algorithms; and sampling uncertainty associated with the statistical design of the NRI survey. To assess input uncertainty, C and N dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007; Del Grosso et al. 2010). Sampling uncertainty is assessed using NRI replicate sampling weights. These data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2015. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator), and random selection of a set of survey weights from the replicates associated with the NRI survey design.

Nitrous oxide emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2015 using the DayCent model. However, note that the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (See Section 6.1, Representation of the U.S. Land Base for more information). Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

For the Tier 3 method, soil N_2O emissions from 2016 to 2019 associated with mineral soils in croplands are estimated using a splicing method that accounts for uncertainty in the original inventory data and the splicing method (See Box 5-4). Annual data are currently available through 2015 (USDA-NRCS 2018a), and the Inventory time series will be updated in the future when new NRI data are released.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil, or made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, is determined for each N source and then divided by the total amount of mineral N in the soil according to the DayCent model simulation. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to N management practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DayCent (e.g., DayCent has not been parametrized to simulate all crop types and some soil types such as *Histosols*). For the Tier 1 method, estimates of direct N_2O emissions from N applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and

mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DayCent simulations. Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DayCent simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic N fertilizer additions for crop areas that are not simulated by DayCent. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS using sales records from 1990 to 2012 (Brakebill and Gronberg 2017). For 2013 through 2015, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 2013 through 2017).[23] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DayCent (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources), the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DayCent.

- Similarly, a process-of-elimination approach is used to estimate manure N additions for crops that are not simulated by DayCent. The total amount of manure available for land application to soils has been estimated with methods described in the Manure Management section (Section 5.2) and annex (Annex 3.11). The amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total annual manure N available for land application (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources). This difference is assumed to be applied to crops that are not simulated by DayCent.

- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics, which are converted from mass of fertilizer to units of N using average organic fertilizer N content, which range between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2017). Commercial fertilizers do include dried manure and biosolids (i.e., treated sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting[24] with the manure N dataset described above and the biosolids (i.e., treated sewage sludge) amendment data discussed later in this section.

- Crop residue N is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2018a), crop production yield statistics (USDA-NASS 2019), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006). N inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total increase in soil mineral N from applied fertilizers and crop residues is multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 method. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions from 2016 to 2019 for Tier 1 mineral soil emissions are estimated using a splicing method that is described in Box 5-4, with the exception of the crop residue N, which is only estimated with the data splicing method for 2019. As with the Tier 3 method, the time series that is based on the splicing methods will be recalculated in a future Inventory report when updated activity data are available.

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[23] The fertilizer consumption data in AAPFCO are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

[24] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., treated sewage sludge) are also included in other datasets in this Inventory. Consequently, the proportions of dried manure and biosolids, which are provided in the reports (TVA 1991 through 1994; AAPFCO 1995 through 2017), are used to estimate the N amounts in dried manure and biosolids. To avoid double counting, the resulting N amounts for dried manure and biosolids are subtracted from the total N in commercial organic fertilizers before estimating emissions using the Tier 1 method.

Tier 1 and 3 Approaches for Direct N₂O Emissions from Mineral Grassland Soils

As with N_2O emissions from croplands, the Tier 3 process-based DayCent model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass or mixed grass/legume forage primarily for livestock grazing. Rangelands are extensive areas of native grassland that are not intensively managed, while pastures are seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or inter-seeding legumes. DayCent is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2018a) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread or manure collected from other animal waste management systems such as lagoons and digesters), and synthetic fertilizer application. Other N inputs are simulated within the DayCent framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach in the Mineral Cropland Soils section. Mineral N fertilization rates are based on data from the Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to support the Inventory. Biological N fixation is simulated within DayCent, and therefore is not an input to the model.

Manure N deposition from grazing animals in PRP systems (i.e., PRP manure N) is a key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI survey location are based on the amount of N excreted by livestock in PRP systems that is estimated in the Manure Management section (See Section 5.2 and Annex 3.10). The total amount of N excreted in each county is divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting rates are a direct input into the DayCent simulations. The N input is subdivided between urine and dung based on a 50:50 split. DayCent simulations of non-federal grasslands accounted for approximately 61 percent of total PRP manure N in aggregate across the country.[25] The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method.

Biosolids (i.e., treated sewage sludge) are assumed to be applied on grasslands. Application of biosolids is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 Wastewater Treatment for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Biosolids data are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DayCent could not be used to simulate the influence of biosolids on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Soil N_2O emission estimates from DayCent are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). There is also sampling uncertainty for the NRI survey that is propagated through the estimate with replicate sampling weights associated with the survey. N_2O emissions for the PRP manure N deposited on federal grasslands and applied biosolids N are estimated using the Tier 1 method by multiplying the N input by the default emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from biosolids N are calculated exclusively at the national scale. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2015 based on the Tier 1 and 3 methods, with the exception of biosolids (discussed below). Emissions from 2016 to 2019 are estimated using a splicing method as described in Box 5-4. As with croplands, estimates for 2016 to 2019 will be

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[25] A small amount of PRP N (less than 1 percent) is deposited in grazed pasture that is in rotation with annual crops, and is reported in the grassland N_2O emissions.

recalculated in a future Inventory when new NRI data are released by USDA. Biosolids application data are compiled through 2019 in this Inventory, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years in the time series without application of the splicing method.

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 method is used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2015 NRI (USDA-NRCS 2018a) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). Temperature data from the PRISM Climate Group (PRISM 2018) are used to subdivide areas into temperate and tropical climates according to the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). Annual NRI data are only available between 1990 and 2015, but the time series was adjusted using data from the Forest Inventory and Analysis Program (USFS 2019) in order to estimate emissions from 2016 to 2018. The land representation data have not been updated for this Inventory so the amount of drained organic soils is assumed to be the same in 2019 as the estimated areas in 2018, and consequently the emissions in 2019 are also assumed to the same as 2018. Further elaboration on the methodology and data used to estimate N_2O emissions from organic soils are described in Annex 3.12.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-16 and Table 5-17).

Indirect N_2O Emissions Associated with Nitrogen Management in Cropland and Grasslands

Indirect N_2O emissions occur when mineral N applied or made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3^-) that is made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DayCent model and IPCC (2006) Tier 1 methods are combined to estimate the amount of N that is volatilized and eventually emitted as N_2O. DayCent is used to estimate N volatilization for land areas whose direct emissions are simulated with DayCent (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method with default IPCC fractions for N subject to volatilization (i.e., N inputs on

croplands not simulated by DayCent, PRP manure N excreted on federal grasslands, and biosolids [i.e., treated sewage sludge] application on grasslands).

The IPCC (2006) default emission factor is multiplied by the amount of volatilized N generated from both DayCent and Tier 1 methods to estimate indirect N_2O emissions occurring following re-deposition of the volatilized N (see Table 5-19). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Tier 1 and 3 Approaches for Indirect N₂O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DayCent model and IPCC (2006) Tier 1 method are combined to estimate the amount of N that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DayCent is used to simulate the amount of N transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff associated with N applications on croplands that are not simulated by DayCent, applications of biosolids on grasslands, and PRP manure N excreted on federal grasslands.

For both the DayCent Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation does not exceed 80 percent of PET (Note: All irrigated systems are assumed to have significant amounts of leaching of N even in drier climates).

For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-19). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Indirect soil N_2O emissions from 2016 to 2019 are estimated using the splicing method that is described in Box 5-4. As with the direct N_2O emissions, the time series will be recalculated in a future Inventory report when new activity data are compiled.

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DayCent; (3) direct emissions estimated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions as well as the components of indirect emissions that are estimated from DayCent are derived from a Monte Carlo Analysis (consistent with IPCC Approach 2), addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). For 2016 to 2019, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-4).

Simple error propagation methods (IPCC 2006) are used to derive confidence intervals for direct emissions estimated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2016 to 2019 (see Box 5-4). Additional details on the uncertainty methods are provided in Annex 3.12.

Table 5-20 shows the combined uncertainty for direct soil N_2O emissions. The estimated emissions ranges from 31 percent below to 31 percent above the 2019 emission estimate of 290.4 MMT CO_2 Eq. The combined uncertainty for indirect soil N_2O emissions ranges from 71 percent below to 154 percent above the 2019 estimate of 54.2 MMT CO_2 Eq.

Table 5-20: Quantitative Uncertainty Estimates of N$_2$O Emissions from Agricultural Soil Management in 2019 (MMT CO$_2$ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N$_2$O Emissions	N$_2$O	290.4	200.7	380.1	-31%	31%
Indirect Soil N$_2$O Emissions	N$_2$O	54.2	16.0	137.5	-71%	154%

Note: Due to lack of data, uncertainties in PRP manure N production, other organic fertilizer amendments, and biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventory reports.

Additional uncertainty is associated with an incomplete estimation of N$_2$O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory currently includes the N$_2$O emissions from mineral fertilizer and PRP N additions in Alaska and Hawaii, and drained organic soils in Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major crop commodity states in the conterminous United States, so the emissions are likely to be small for the other sources of N (e.g., crop residue inputs), which are not currently included in the Inventory.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. DayCent results for N$_2$O emissions and NO$_3^-$ leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data for cropland are available for 64 sites representing 796 different combinations of fertilizer treatments and cultivation practices, and measurement data for grassland are available for 13 sites representing 36 different management treatments. Nitrate leaching data are available for 12 sites, representing 279 different combinations of fertilizer treatments and tillage practices. In general, DayCent predicted N$_2$O emission and nitrate leaching for these sites reasonably well. See Annex 3.12 for more detailed information about the comparisons.

Spreadsheets containing input data and probability distribution functions required for DayCent simulations of croplands and grasslands and unit conversion factors have been checked, in addition to the program scripts that are used to run the Monte Carlo uncertainty analysis. Links between spreadsheets have also been checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed.

Recalculations Discussion

One improvement has been implemented in this Inventory leading to the need for recalculations. This improvement was an update to the time series of PRP and manure N available for application to soils, in order to be consistent with the data generated for the Manure Management section of this Inventory. The surrogate data method was also applied to re-estimate N$_2$O emissions from 2016 to 2018. These changes resulted in an average increase in emissions of 0.1 percent from 1990 to 2018 relative to the previous Inventory.

Planned Improvements

A key improvement for a future Inventory will be to incorporate additional management activity data from the USDA-NRCS Conservation Effects Assessment Project survey. This survey has compiled new data in recent years that will be available for the Inventory analysis by next year. The latest land use data will also be incorporated from the USDA National Resources Inventory and related management data from USDA-ERS ARMS surveys.

Several planned improvements are underway associated with improving the DayCent biogeochemical model. These improvements include a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DayCent with additional model calibration. Model development is underway to represent the influence of nitrification inhibitors and slow-release fertilizers (e.g., polymer-coated fertilizers) on N_2O emissions. Experimental study sites will continue to be added for quantifying model structural uncertainty. Studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority.

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see Section 5.7). Alaska and Hawaii are not included for all sources in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii, synthetic fertilizer and PRP N amendments for grasslands in Alaska and Hawaii. There is also an improvement based on updating the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factor in the 2013 Supplement to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013).

In addition, there is a planned improvement associated with implementation of the Tier 1 method. Specifically, soil N_2O emissions will be estimated and reported for N mineralization from soil organic matter decomposition that is accelerated with *Forest Land Converted to Cropland* and *Grassland Converted to Cropland*. A review of available data on biosolids (i.e., treated sewage sludge) application will also be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

These improvements are expected to be completed for the next full Inventory analysis (i.e., 2022 submission to the UNFCCC, 1990 through 2020 Inventory). However, the timeline may be extended if there are insufficient resources to fund all or part of these planned improvements.

5.5 Liming (CRF Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production, etc.) are reported in the IPPU chapter. Emissions from liming of soils have fluctuated between 1990 and 2019 in the United States, ranging from 2.2 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. across the entire time series. In 2019, liming of soils in the United States resulted in emissions of 2.4 MMT CO_2 Eq. (0.7 MMT C), representing a 52 percent decrease in emissions since 1990 (see Table 5-21 and Table 5-22). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-21: Emissions from Liming (MMT CO₂ Eq.)

Source	1990	2005	2015	2016	2017	2018	2019
Limestone	4.1	3.9	3.5	2.8	2.9	2.0	2.2
Dolomite	0.6	0.4	0.3	0.3	0.2	0.2	0.2

Total	**4.7**		**4.3**		**3.7**	**3.1**	**3.1**	**2.2**	**2.4**

Note: Totals may not sum due to independent rounding.

Table 5-22: Emissions from Liming (MMT C)

Source	1990		2005		2015	2016	2017	2018	2019
Limestone	1.1		1.1		0.9	0.8	0.8	0.6	0.6
Dolomite	0.2		0.1		0.1	0.1	0.1	0.1	0.1
Total	**1.3**		**1.2**		**1.0**	**0.8**	**0.8**	**0.6**	**0.7**

Note: Totals may not sum due to independent rounding.

Methodology

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite, which are applied to soils (see Table 5-23), were multiplied by CO_2 emission factors from West and McBride (2005). These country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008) (See Box 5-5).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016, 2017, 2020a), as well as preliminary data that will eventually be published in the Minerals Yearbook for the latter part of the time series (Willett 2019, 2020b). Data for the final year of the inventory is based on the *Mineral Industry Surveys*, as discussed below (USGS 2020). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "estimated" production).

Box 5-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) emission default factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rives and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton C/metric ton dolomite). For comparison, the 2019 U.S. emission estimate from liming of soils is 2.4 MMT CO_2 Eq. using the country-specific factors. In contrast, emissions would be estimated at 5.0 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on "specified" limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the "unspecified" and "estimated" categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, and 2019 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2019 data, 2018 fractions were applied to a 2019 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2020* (USGS 2020).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1996 and by the USGS from 1997 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-23: Applied Minerals (MMT)

Mineral	1990		2005		2015	2016	2017	2018	2019
Limestone	19.0		18.1		16.0	13.0	13.4	9.4	10.2
Dolomite	2.4		1.9		1.2	1.1	0.8	0.9	1.0

Uncertainty and Time-Series Consistency

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-24. Carbon dioxide emissions from carbonate lime application to soils in 2019 were estimated to be between -0.27 and 4.61 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 111 percent below to 88 percent above the 2019 emission estimate of 2.4 MMT CO_2 Eq. Note that there is a small probability of a negative emissions value leading to a net uptake of CO_2 from the atmosphere. Net uptake occurs due to the dominance of the carbonate lime dissolving in carbonic acid rather than nitric acid (West and McBride 2005).

Table 5-24: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Liming (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO₂	2.4	(0.27)	4.61	-111%	88%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The quality control effort focused on the Tier 1 procedures for this Inventory. No errors were found.

Recalculations Discussion

An adjustment was made in the current Inventory to improve the results; limestone and dolomite application data for 2018 were updated with the recently published data from USGS (2020), rather than approximated by a ratio method, which was used in the previous Inventory. With this revision in the activity data, the emissions decreased by 28.6 percent for 2018 relative to the previous Inventory.

5.6 Urea Fertilization (CRF Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to greenhouse gas emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States is 5.3 MMT CO₂ Eq. (1.5 MMT C) in 2019 (Table 5-25 and Table 5-26). Carbon dioxide emissions have increased by 121 percent between 1990 and 2019 due to an increasing amount of urea that is applied to soils. The variation in emissions across the time series is driven by differences in the amounts of fertilizer applied to soils each year. Carbon dioxide emissions associated with urea that is used for non-agricultural purposes are reported in the IPPU chapter (Section 4.6).

Table 5-25: CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq.)

Source	1990		2005		2015	2016	2017	2018	2019
Urea Fertilization	2.4		3.5		4.7	4.9	5.1	5.2	5.3

Table 5-26: CO₂ Emissions from Urea Fertilization (MMT C)

Source	1990		2005		2015	2016	2017	2018	2019
Urea Fertilization	0.7		1.0		1.3	1.3	1.4	1.4	1.5

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The method assumes that C in the urea is released after application to soils and converted to CO_2. The annual amounts of urea applied to croplands (see Table 5-27) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2018).[26] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of C per metric ton of urea), which is equal to the C content of urea on an atomic weight basis. The calculations were made using a Monte Carlo analysis as described in the Uncertainty section below.

Fertilizer sales data are reported in fertilizer years (July previous year through June current year) so a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year.

Fertilizer sales data for the 2016 through 2019 fertilizer years were not available for this Inventory. Therefore, urea application in the 2016 through 2019 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2011 through 2015) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-state and inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year (Table 5-27) data using the method described above.

Table 5-27: Applied Urea (MMT)

	1990		2005		2015	2016	2017	2018	2019
Urea Fertilizer[a]	3.3		4.8		6.4	6.7	6.9	7.1	7.3

[a] These numbers represent amounts applied to all agricultural land, including *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Settlements Remaining Settlements*, *Land Converted to Settlements*, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land,* as it is not currently possible to apportion the data by land-use category.

Uncertainty and Time-Series Consistency

An Approach 2 Monte Carlo analysis is conducted as described by the IPCC (2006). The largest source of uncertainty is the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The uncertainty surrounding this factor incorporates the possibility that some of the C may not be emitted to the atmosphere, and therefore the uncertainty range is set from 50 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data have uncertainty that is represented as a normal density. Due to the highly skewed distribution of the resulting emissions from the Monte Carlo uncertainty analysis, the estimated emissions are based on the analytical solution to the equation, and the confidence interval is approximated based on the values at 2.5 and 97.5 percentiles.

Carbon dioxide emissions from urea fertilization of agricultural soils in 2019 are estimated to be between 3.06 and 5.51 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2019 emission estimate of 5.3 MMT CO_2 Eq. (Table 5-28).

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[26] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Table 5-28: Quantitative Uncertainty Estimates for CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO₂	5.3	3.06	5.51	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. There is uncertainty surrounding the assumptions underlying conversion of fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with a corresponding increase or decrease in the value for the subsequent year. In addition, there is uncertainty regarding the fate of C in urea that is incorporated into solutions of urea ammonium nitrate (UAN) fertilizer. Emissions of CO₂ from UAN applications to soils are not estimated in the current Inventory (see Planned Improvements).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies are described in the Introduction and Methodology sections.

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, consistent with the U.S. Inventory QA/QC plan. One quality control issue was raised by the expert review team (ERT) from the UNFCCC for this emission source. In the previous (i.e., 1990 through 2018) Inventory, estimates of CO₂ emissions were based on the results from the Monte Carlo uncertainty analysis. Specifically, the mode from the Monte Carlo uncertainty analysis was used as the most probable estimate of emissions. The mode differs from the analytical solution to the equation due to the pattern in the probability distribution for CO₂ emissions from the Monte Carlo uncertainty analysis, which combined a normal density for the urea application data with the right triangle distribution for the emission factor. For this Inventory, the analytical solution has been adopted as the estimate of CO₂ emissions for urea fertilization to be consistent with recommendations from ERT. The ERT considered the analytical solution to be more representative of the emissions than the mode from the Monte Carlo uncertainty analysis.

Recalculations Discussion

Emissions estimates were derived directly from the Monte Carlo uncertainty analysis in the previous Inventory as discussed in the QA/QC and Verification section. For this Inventory, the entire time series was recalculated using the analytical solution rather than the mode from the Monte Carlo uncertainty analysis. This change in emission estimates averaged about 15 percent higher across the time series compared to the previous Inventory.

Planned Improvements

A key planned improvement is to incorporate Urea Ammonium Nitrate (UAN) in the estimation of Urea CO₂ emissions. Activity data for UAN have been identified, but additional information is needed to fully incorporate this type of fertilizer into the analysis, which will be completed in a future Inventory.

5.7 Field Burning of Agricultural Residues (CRF Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. Field burning of crop residues is not considered a net source of CO_2 emissions because the C released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop. However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues commonly occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane and wheat (McCarty 2009). In 2019, CH_4 and N_2O emissions from field burning of agricultural residues were 0.4 MMT CO_2 Eq. (17 kt) and 0.2 MMT CO_2 Eq. (1 kt), respectively (Table 5-29 and Table 5-30). Annual emissions of CH_4 and N_2O have increased from 1990 to 2019 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some of the crop types.

Table 5-29: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990	2005	2015	2016	2017	2018	2019
CH₄	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Maize	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
N₂O	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Maize	+	+	0.1	0.1	0.1	0.1	0.1
Rice	+	+	+	+	+	+	+
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1

	1990		2005		2015	2016	2017	2018	2019
Barley	+		+		+	+	+	+	+
Oats	+		+		+	+	+	+	+
Other Small Grains	+		+		+	+	+	+	+
Sorghum	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Grass Hay	+		+		+	+	+	+	+
Legume Hay	+		+		+	+	+	+	+
Peas	+		+		+	+	+	+	+
Sunflower	+		+		+	+	+	+	+
Tobacco	+		+		+	+	+	+	+
Vegetables	+		+		+	+	+	+	+
Chickpeas	+		+		+	+	+	+	+
Dry Beans	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Peanuts	+		+		+	+	+	+	+
Soybeans	+		+		+	+	+	+	+
Potatoes	+		+		+	+	+	+	+
Sugarbeets	+		+		+	+	+	+	+
Total	**0.5**		**0.6**		**0.6**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 5-30: CH₄, N₂O, CO, and NOₓ Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990		2005		2015	2016	2017	2018	2019
CH₄	**15**		**17**		**18**	**17**	**17**	**17**	**17**
Maize	2		4		5	5	5	5	5
Rice	3		3		3	2	3	2	3
Wheat	6		6		5	5	5	5	5
Barley	+		+		+	+	+	+	+
Oats	+		+		+	+	+	+	+
Other Small Grains	+		+		+	+	+	+	+
Sorghum	+		+		+	+	+	+	+
Cotton	1		2		1	1	1	1	1
Grass Hay	+		+		+	+	+	+	+
Legume Hay	+		+		+	+	+	+	+
Peas	+		+		+	+	+	+	+
Sunflower	+		+		+	+	+	+	+
Tobacco	+		+		+	+	+	+	+
Vegetables	+		+		+	+	+	+	+
Chickpeas	+		+		+	+	+	+	+
Dry Beans	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Peanuts	+		+		+	+	+	+	+
Soybeans	1		2		2	2	2	2	2
Potatoes	+		+		+	+	+	+	+
Sugarbeets	+		+		+	+	+	+	+
N₂O	**1**		**1**		**1**	**1**	**1**	**1**	**1**

Maize	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
CO	**315**	**363**	**342**	**340**	**339**	**338**	**337**
NOx	**13**	**15**	**14**	**14**	**14**	**14**	**14**

+ Does not exceed 0.5 kt.
Note: Totals may not sum due to independent rounding.

Methodology

A country-specific Tier 2 method is used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2014 (for more details comparing the country-specific approach to the IPCC (2006) default approach, see Box 5-6), and a data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2019. The following equation is used to estimate the amounts of C and N released ($R_i, where\ i\ is\ C\ or\ N$) from burning.

$$R_i = CP \times RCR \times DMF \times F_i \times FB \ \times CE$$

$$FB \ = \frac{AB}{CAH}$$

where,

Crop Production (CP)	= Annual production of crop, by state, kt crop production
Residue: Crop Ratio (RCR)	= Amount of residue produced per unit of crop production, kt residue/kt crop production
Dry Matter Fraction (DMF)	= Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
Fraction C or N (F_i)	= Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
Fraction Burned (FB)	= Proportion of residue biomass consumed, unitless

Combustion Efficiency (CE)	= Proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively, unitless
Area Burned (AB)	= Total area of crop burned, by state, ha
Crop Area Harvested (CAH)	= Total area of crop harvested, by state, ha

Crop production data are available by state and year from USDA (2019) for twenty-one crops that are burned in the conterminous United States, including maize, rice, wheat, barley, oats, other small grains, sorghum, cotton, grass hay, legume hay, peas, sunflower, tobacco, vegetables, chickpeas, dry beans, lentils, peanuts, soybeans, potatoes, and sugarbeets.[27] Crop area data are based on the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields is multiplied by the NRI crop areas. The production data for the crop types are presented in Table 5-31. Alaska and Hawaii are not included in the current analysis, but there is a planned improvement to estimate residue burning emissions for these two states in a future Inventory.

The amount of elemental C or N released through oxidation of the crop residues is used in the following equation to estimate the amount of CH_4, CO, N_2O, and NO_x emissions (E_g, where g is the specific gas, i.e., CH_4, CO, N_2O, and NO_x) from the Field Burning of Agricultural Residues:

$$E_g = R_i \times EF_g \times CF$$

where,

| Emission ratio (EF_g) | = emission ratio by gas, g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released |
| Conversion Factor (CF) | = conversion by molecular weight ratio of CH_4-C to C (16/12), CO-C to C (28/12), N_2O-N to N (44/28), or NO_x-N to N (30/14) |

Box 5-6: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather emission rates related to the amount of C and N in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from twenty-one crops.

A comparison of the methods in the current Inventory and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

$$Emissions\ (kt) = AB \times (M_B \times C_f) \times G_{ef} \times 10^{-6}$$

where,

| Area Burned (AB) | = Total area of crop burned (ha) |
| Mass of Fuel ($M_B \times C_f$) | = IPCC (2006) default carbon fractions with fuel biomass consumption U.S.- |

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[27] Sugarcane and Kentucky bluegrass (produced on farms for turf grass installations) may have small areas of burning that are not captured in the sample of locations that were used in the remote sensing analysis (see Planned Improvements).

The IPCC (2006) Tier 1 method approach resulted in 33 percent lower emissions of CH_4 and 53 percent lower emissions of N_2O compared to this Inventory. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific C and N content of the fuel, which is converted into CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Table 5-31: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2013	2014
Maize	296,065	371,256	436,565	453,524
Rice	9,543	11,751	10,894	12,380
Wheat	79,805	68,077	67,388	62,602
Barley	9,281	5,161	4,931	5,020
Oats	5,969	2,646	1,806	2,042
Other Small Grains	2,651	2,051	1,902	2,492
Sorghum	23,687	14,382	18,680	18,436
Cotton	4,605	6,106	3,982	4,396
Grass Hay	44,150	49,880	45,588	46,852
Legume Hay	90,360	91,819	79,669	82,844
Peas	51	660	599	447
Sunflower	1,015	1,448	987	907
Tobacco	1,154	337	481	542
Vegetables	0	1,187	1,844	2,107
Chickpeas	0	5	0	0
Dry Beans	467	1,143	1,110	1,087
Lentils	0	101	72	76
Peanuts	1,856	2,176	2,072	2,735
Soybeans	56,612	86,980	94,756	110,560
Potatoes	18,924	20,026	20,234	19,175
Sugarbeets	24,951	25,635	31,890	31,737

Note: The amount of crop production has not been compiled for 2015 to 2019 so a data splicing method is used to estimate emissions for this portion of the time series.

The area burned is determined based on an analysis of remote sensing products (McCarty et al. 2009, 2010, 2011). The presence of fires has been analyzed at 3600 survey locations in the NRI from 1990 to 2002 with LANDFIRE data products developed from 30 m Landsat imagery (LANDFIRE 2014), and from 2003 through 2014 using 1 km Moderate Resolution Imaging Spectroradiometer imagery (MODIS) Global Fire Location Product (MCD14ML) using combined observations from Terra and Aqua satellites (Giglio et al. 2006). A sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states.

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[28] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the Inventory.

For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events. Several variables are tested in the logistical regression including a) the historical level of burning in each state (high, medium or low levels of burning) based on an analysis by McCarty et al. (2011), b) year that state laws limit burning of fields, in addition to c) mean annual precipitation and mean annual temperature from a 4-kilometer gridded product from the PRISM Climate Group (2015). A K-fold model fitting procedure is used due to low frequency of burning and likelihood that outliers could influence the model fit. Specifically, the model is trained with a random selection of sample locations and evaluated with the remaining sample. This process is repeated ten times to select a model that is most common among the set of ten, and avoid models that appear to be influenced by outliers due to the random draw of survey locations for training the model. In order to address uncertainty, a Monte Carlo analysis is used to sample the parameter estimates for the logistical regression model and produce one thousand estimates of burning for each crop in the remaining forty-two states included in this Inventory. State-level area burned data are divided by state-level crop area data to estimate the percent of crop area burned by crop type for each state. Table 5-32 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

Table 5-32: U.S. Average Percent Crop Area Burned by Crop (Percent)

Crop	1990		2005		2013	2014
Maize	+%		+%		+%	+%
Rice	8%		8%		4%	6%
Wheat	1%		2%		2%	1%
Barley	1%		+%		1%	1%
Oats	1%		1%		2%	1%
Other Small Grains	1%		1%		1%	1%
Sorghum	1%		1%		1%	1%
Cotton	1%		1%		1%	1%
Grass Hay	+%		+%		+%	+%
Legume Hay	+%		+%		+%	+%
Peas	+%		+%		+%	+%
Sunflower	+%		+%		+%	+%
Tobacco	2%		2%		3%	3%
Vegetables	0%		+%		+%	+%
Chickpeas	0%		1%		0%	0%
Dry Beans	1%		1%		+%	+%
Lentils	0%		+%		+%	+%
Peanuts	3%		3%		3%	3%
Soybeans	+%		+%		1%	1%
Potatoes	+%		+%		+%	+%
Sugarbeets	+%		+%		+%	+%

+ Does not exceed 0.5 percent

Additional parameters are needed to estimate the amount of burning, including residue: crop ratios, dry matter fractions, carbon fractions, nitrogen fractions and combustion efficiency. Residue: crop product mass ratios, residue dry matter fractions, and the residue N contents are obtained from several sources (IPCC 2006 and sources at bottom of Table 5-33). The residue C contents for all crops are based on IPCC (2006) default value for herbaceous biomass. The combustion efficiency is assumed to be 90 percent for all crop types (IPCC/UNEP/OECD/IEA 1997). See Table 5-33 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases are based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-34).

Table 5-33: Parameters for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Combustion Efficiency (Fraction)
Maize	0.707	0.56	0.47	0.01	0.90
Rice	1.340	0.89	0.47	0.01	0.90
Wheat	1.725	0.89	0.47	0.01	0.90
Barley	1.181	0.89	0.47	0.01	0.90
Oats	1.374	0.89	0.47	0.01	0.90
Other Small Grains	1.777	0.88	0.47	0.01	0.90
Sorghum	0.780	0.60	0.47	0.01	0.90
Cotton	7.443	0.93	0.47	0.01	0.90
Grass Hay	0.208	0.90	0.47	0.02	0.90
Legume Hay	0.290	0.67	0.47	0.01	0.90
Peas	1.677	0.91	0.47	0.01	0.90
Sunflower	1.765	0.88	0.47	0.01	0.90
Tobacco	0.300	0.87	0.47	0.01	0.90
Vegetables	0.708	0.08	0.47	0.01	0.90
Chickpeas	1.588	0.91	0.47	0.01	0.90
Dry Beans	0.771	0.90	0.47	0.01	0.90
Lentils	1.837	0.91	0.47	0.02	0.90
Peanuts	1.600	0.94	0.47	0.02	0.90
Soybeans	1.500	0.91	0.47	0.01	0.90
Potatoes	0.379	0.25	0.47	0.02	0.90
Sugarbeets	0.196	0.22	0.47	0.02	0.90

Notes:

Chickpeas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Cotton: Combined sources (Heitholt et al. 1992; Halevy 1976; Wells and Meredith 1984; Sadras and Wilson 1997; Pettigrew and Meredith 1997; Torbert and Reeves 1994; Gerik et al. 1996; Brouder and Cassmen 1990; Fritschi et al. 2003; Pettigrew et al. 2005; Bouquet and Breitenbeck 2000; Mahroni and Aharonov 1964; Bange and Milroy 2004; Hollifield et al. 2000; Mondino et al. 2004; Wallach et al. 1978).

Lentils: IPCC (2006), Table 11.2; Beans & pulses.

Peas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Peanuts: IPCC (2006); Table 11.2; Root ratio and belowground N content values are for Root crops, other.

Sugarbeets: IPCC (2006); Table 11.2; values are for Tubers.

Sunflower: IPCC (2006), Table 11.2; values are for Grains.

Sugarcane: combined sources (Wiedenfels 2000, Dua and Sharma 1976; Singels & Bezuidenhout 2002; Stirling et al. 1999; Sitompul et al. 2000).

Tobacco: combined sources (Beyaert 1996; Moustakas and Ntzanis 2005; Crafts-Brandner et al. 1994; Hopkinson 1967; Crafts-Brandner et al. 1987).

Vegetables (Combination of carrots, lettuce/cabbage, melons, onions, peppers and tomatoes):
  Carrots: McPharlin et al. (1992); Gibberd et al. (2003); Reid and English (2000); Peach et al. (2000); see IPCC Tubers for R:S and N fraction.
  Lettuce, cabbage: combined sources (Huett and Dettman 1991; De Pinheiro Henriques & Marcelis 2000; Huett and Dettman 1989; Peach et al. 2000; Kage et al. 2003; Tan et al. 1999; Kumar et al. 1994; MacLeod et al. 1971; Jacobs et al. 2004; Jacobs et al. 2001; Jacobs et al. 2002); values from IPCC Grains used for N fraction.
  Melons: Valantin et al. (1999); squash for R:S; IPCC Grains for N fraction.
  Onion: Peach et al. (2000), Halvorson et al. (2002); IPCC (2006) Tubers for N fraction.
  Peppers: combined sources (Costa and Gianquinto 2002; Marcussi et al. 2004; Tadesse et al. 1999; Diaz-Perez et al. 2008); IPCC Grains for N fraction.

Tomatoes: Scholberg et al. (2000a,b); Akintoye et al. (2005); values for AGR-N and BGR-N are from Grains.

Table 5-34: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

For this Inventory, new activity data on the burned areas have not been analyzed for 2015 to 2019. To complete the emissions time series, a linear extrapolation of the trend is applied to estimate the emissions in the last five years of the inventory. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH_4, N_2O, CO and NO_x for the last five years in the time series from 2015 to 2019 (Brockwell and Davis 2016). The Tier 2 method described previously will be applied to recalculate the emissions for the last five years in the time series (2015 to 2019) in a future Inventory.

Uncertainty and Time-Series Consistency

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2019. The linear regression ARMA model produced estimates of the upper and lower bounds to quantify uncertainty (Table 5-35), and the results are summarized in Table 5-35. Methane emissions from field burning of agricultural residues in 2019 are between 0.35 and 0.50 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 18 percent below and 18 percent above the 2019 emission estimate of 0.43 MMT CO_2 Eq. Nitrous oxide emissions are between 0.16 and 0.22 MMT CO_2 Eq., or approximately 17 percent below and 17 percent above the 2019 emission estimate of 0.19 MMT CO_2 Eq.

Table 5-35: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.4	0.35	0.50	-18%	18%
Field Burning of Agricultural Residues	N_2O	0.2	0.16	0.22	-17%	17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation) and sugarcane.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in the Introduction and Methodology sections.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues is implemented with Tier 1 analyses, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The previous Inventory included a term for burning efficiency that is not found in the IPCC/UNEP/OECD/IEA (1997) method. This term has been removed based on a QA/QC initiated by the UN Expert Review Team. In addition, the combustion efficiency term has been set to 90 percent to be consistent with the Tier 1 method in IPCC/UNEP/OECD/IEA (1997).

Recalculations Discussion

Methodological recalculations are associated with two methodological revisions, a) removing the burning efficiency term and b) adopting the combustion efficiency value in IPCC/UNEP/OECD/IEA (1997) (See QA/QC and Verification Section for more information). As a result of these two revisions, the emissions increased on average across the time series by 10 percent and 9 percent for CH_4 and N_2O, respectively. The absolute increases in emissions are 0.4 MMT CO_2 Eq. and 0.2 MMT CO_2 Eq. for CH_4 and N_2O, respectively.

Planned Improvements

A key planned improvement is to estimate the emissions associated with field burning of agricultural residues in the states of Alaska and Hawaii. In addition, a new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including Agricultural Soil Management, *Cropland Remaining Cropland*, and *Land Converted to Cropland* chapters of the Inventory. The method is based on simulating burning events directly within the DayCent process-based model framework using information derived from remote sensing fire products as described in the Methodology section. This improvement will lead to greater consistency in the methods for across sources, ensuring mass balance of C and N in the Inventory analysis.

As previously noted in this chapter, remote sensing data were used in combination with a resource survey to estimate non-CO_2 emissions and these data did not allow identification of burning of sugarcane (see Annex 5). In addition, during the Public Review period of this current (1990 through 2019) Inventory, EPA received feedback on this category/crop type which provided average estimates of emissions of sugarcane burning found in academic literature. EPA plans to assess the information identified in feedback, as well as other available activity data, as part of future inventory improvements.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land-use types including: Forest Land, Cropland, Grassland, Wetlands, and Settlements (as well as Other Land).

The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from *Land Converted to Forest Land* are included for aboveground biomass, belowground biomass, dead wood, litter, and C stock changes from mineral soils, while C stock changes from drained organic soils and the non-CO_2 emissions from *Land Converted to Forest Land* are included in the fluxes from *Forest Land Remaining Forest Land* as it is not currently possible to separate the fluxes by conversion category.

Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland*, and *Land Converted to Grassland*. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic C stocks in mineral and organic soils due to land use and management, and for the subcategories of *Forest Land Converted to Cropland* and *Forest Land Converted to Grassland*, the changes in aboveground biomass, belowground biomass, dead wood, and litter C stocks are also reported. The greenhouse gas flux from *Grassland Remaining Grassland* also includes estimates of non-CO_2 emissions from grassland fires occurring on both *Grassland Remaining Grassland* and *Land Converted to Grassland*.

Fluxes from *Wetlands Remaining Wetlands* include changes in C stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter soil C stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. Estimates for *Land Converted to Wetlands* include aboveground and belowground biomass, dead organic matter and soil C stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands.

Fluxes from *Settlements Remaining Settlements* include changes in C stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from *Land Converted to Settlements* includes changes in C stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the C

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[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory *Forest Land Converted to Settlements.*

In 2019 the land use, land-use change, and forestry (LULUCF) sector resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.7 MMT CO_2 Eq. (221.6 MMT C).[2] This represents an offset of approximately 12.4 percent of total (i.e., gross) greenhouse gas emissions in 2019. Emissions of CH_4 and N_2O from LULUCF activities in 2019 were 23.5 MMT CO_2 Eq. and represent 0.4 percent of total greenhouse gas emissions.[3] In 2019 the overall net flux from LULUCF resulted in a removal of 789.2 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land-use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2019 time series are shown in Figure 6-2.

Figure 6-1: 2019 LULUCF Chapter Greenhouse Gas Sources and Sinks
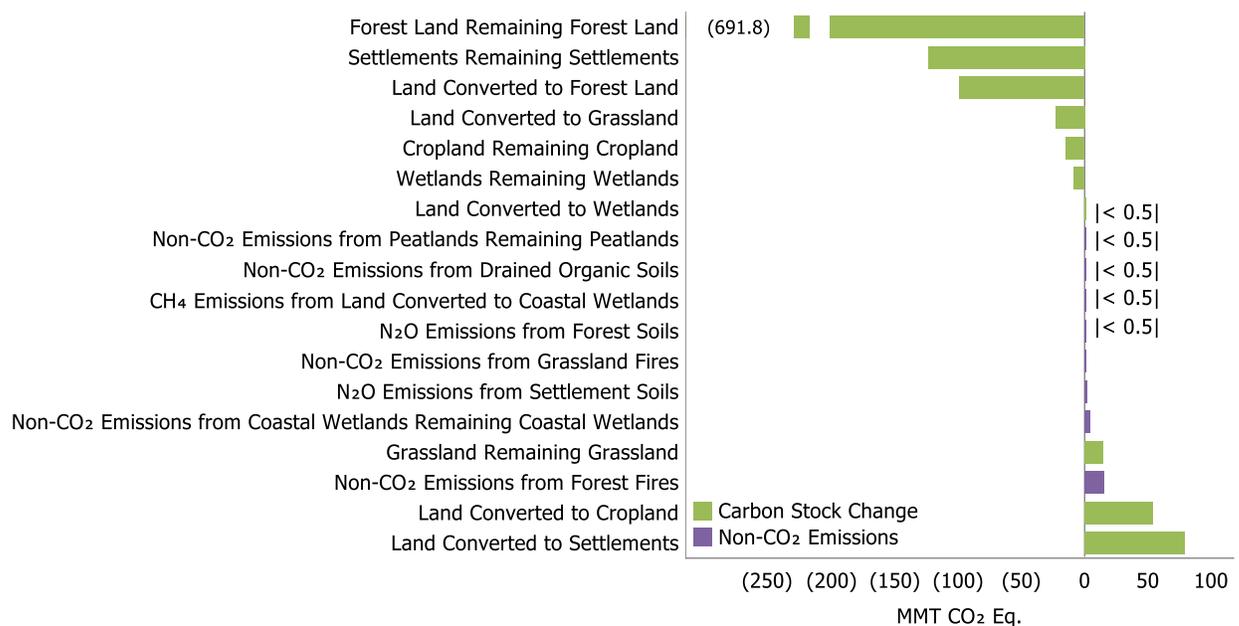
Note: Parentheses indicate net sequestration.

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[2] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 6-2: Trends in Emissions and Removals (Net CO₂ Flux) from Land Use, Land-Use Change, and Forestry[a]
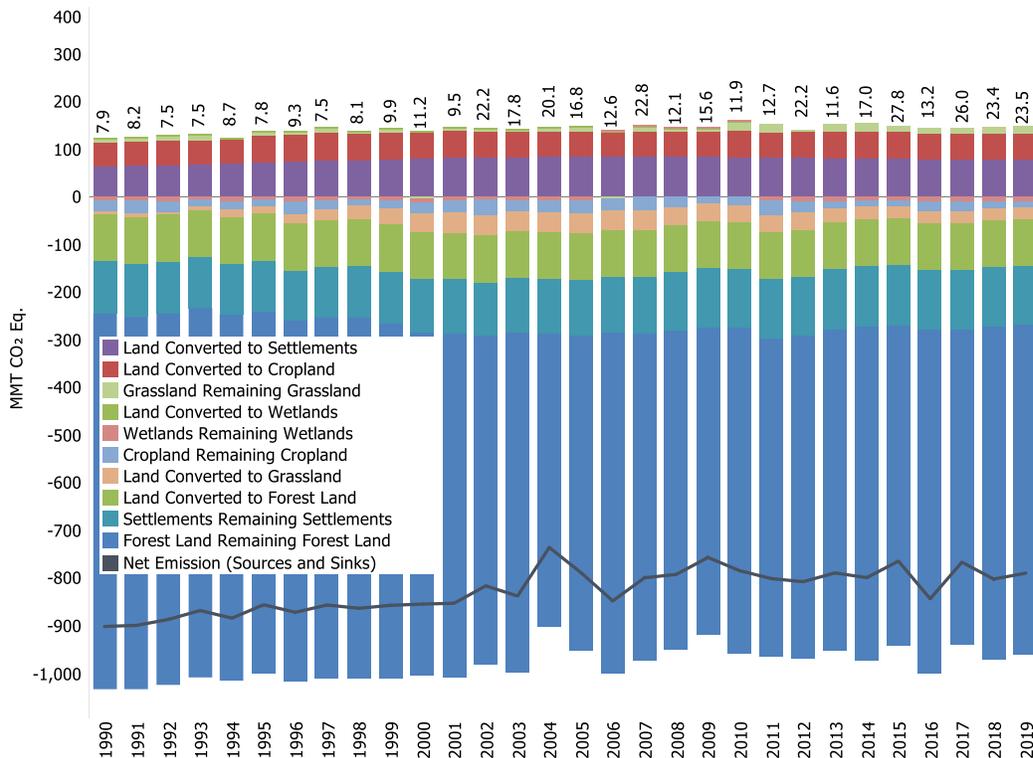
[a] In Figure 6-2, the values above stacked bars represent only non-CO₂ LULUCF emissions. LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands; and N_2O emissions from Forest Soils and Settlement Soils.

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO₂ Eq.)

Land-Use Category	1990		2005		2015	2016	2017	2018	2019
Forest Land Remaining Forest Land	**(785.9)**		**(652.8)**		**(650.6)**	**(715.7)**	**(640.9)**	**(682.4)**	**(675.5)**
Changes in Forest Carbon Stocks[a]	(787.6)		(661.5)		(671.4)	(721.9)	(659.7)	(698.6)	(691.8)
Non-CO₂ Emissions from Forest Fires[b]	1.5		8.2		20.3	5.6	18.3	15.7	15.7
N₂O Emissions from Forest Soils[c]	0.1		0.5		0.5	0.5	0.5	0.5	0.5
Non-CO₂ Emissions from Drained Organic Soils[d]	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.2)**		**(98.7)**		**(98.9)**	**(99.0)**	**(99.1)**	**(99.1)**	**(99.1)**
Changes in Forest Carbon Stocks[e]	(98.2)		(98.7)		(98.9)	(99.0)	(99.1)	(99.1)	(99.1)
Cropland Remaining Cropland	**(23.2)**		**(29.0)**		**(12.8)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)		(29.0)		(12.8)	(22.7)	(22.3)	(16.6)	(14.5)
Land Converted to Cropland	**51.8**		**52.2**		**56.1**	**54.4**	**54.6**	**54.3**	**54.2**
Changes in all Ecosystem Carbon Stocks[f]	51.8		52.2		56.1	54.4	54.6	54.3	54.2
Grassland Remaining Grassland	**8.5**		**10.7**		**13.8**	**10.4**	**11.9**	**12.3**	**15.1**
Changes in Mineral and Organic Soil Carbon Stocks	8.3		10.0		13.1	9.8	11.3	11.7	14.5
Non-CO₂ Emissions from Grassland Fires[g]	0.2		0.7		0.7	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(6.2)**		**(40.1)**		**(23.9)**	**(24.0)**	**(24.4)**	**(24.1)**	**(23.2)**
Changes in all Ecosystem Carbon Stocks[f]	(6.2)		(40.1)		(23.9)	(24.0)	(24.4)	(24.1)	(23.2)

Wetlands Remaining Wetlands	**(3.5)**	**(2.6)**	**(4.1)**	**(4.1)**	**(4.0)**	**(4.0)**	**(4.0)**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.8	0.7	0.8	0.8	0.8
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands	**0.7**	**0.7**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Changes in Biomass, DOM, and Soil Carbon Stocks	0.4	0.4	(0.1)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(123.7)**	**(121.5)**	**(121.4)**	**(121.2)**	**(121.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	15.7	16.0	16.0	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(130.4)	(129.8)	(129.8)	(129.8)	(129.8)
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(11.1)	(10.0)	(9.8)	(9.8)	(10.2)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.2	2.3	2.4	2.4
Land Converted to Settlements	**62.9**	**85.0**	**80.1**	**79.4**	**79.3**	**79.3**	**79.2**
Changes in all Ecosystem Carbon Stocks[f]	62.9	85.0	80.1	79.4	79.3	79.3	79.2
LULUCF Emissions[i]	**7.9**	**16.8**	**27.8**	**13.2**	**26.0**	**23.4**	**23.5**
LULUCF Carbon Stock Change[j]	**(908.7)**	**(804.8)**	**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
LULUCF Sector Net Total[k]	**(900.8)**	**(788.1)**	**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[g] Estimates include CH_4 and N_2O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements* because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[j] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

The C stock change and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total C sequestration in the LULUCF sector decreased by approximately 10.6 percent between 1990 and 2019. This decrease was primarily due to a decline in the rate of net C accumulation in Forest Land and

Cropland Remaining Cropland, as well as an increase in emissions from *Land Converted to Settlements*.[4] Specifically, there was a net C accumulation in *Settlements Remaining Settlements*, which increased from 1990 to 2019, while the net C accumulation in *Forest Land Remaining Forest Land* and *Cropland Remaining Cropland* slowed over this period. Net C accumulation remained steady from 1990 to 2019 in *Land Converted to Forest Land, Land Converted to Cropland*, *Wetlands Remaining Wetlands,* and *Land Converted to Wetlands*, while net C accumulation fluctuated in *Grassland Remaining Grassland.* Net C accumulation from *Land Converted to Grassland* increased from 1990 to 2019.

Forest fires were the largest source of CH_4 emissions from LULUCF in 2019, totaling 9.5 MMT CO_2 Eq. (379 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8 MMT CO_2 Eq. (153 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). *Land Converted to Wetlands* resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (7 kt of CH_4). *Drained Organic Soils* on forest lands and *Peatlands Remaining Peatlands* resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

For N_2O emissions, forest fires were also the largest source from LULUCF in 2019, totaling 6.2 MMT CO_2 Eq. (21 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2019 totaled to 2.4 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 20.2 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2019 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions. Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and drained organic soils on forest lands resulted in N_2O emissions of 0.1 MMT CO_2 Eq. each (less than 0.5 kt of N_2O), and *Peatlands Remaining Peatlands* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO$_2$ Eq.)

Gas/Land-Use Category	1990		2005		2015	2016	2017	2018	2019
Carbon Stock Change[a]	**(908.7)**		**(804.8)**		**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
Forest Land Remaining Forest Land	(787.6)		(661.5)		(671.4)	(721.9)	(659.7)	(698.6)	(691.8)
Land Converted to Forest Land	(98.2)		(98.7)		(98.9)	(99.0)	(99.1)	(99.1)	(99.1)
Cropland Remaining Cropland	(23.2)		(29.0)		(12.8)	(22.7)	(22.3)	(16.6)	(14.5)
Land Converted to Cropland	51.8		52.2		56.1	54.4	54.6	54.3	54.2
Grassland Remaining Grassland	8.3		10.0		13.1	9.8	11.3	11.7	14.5
Land Converted to Grassland	(6.2)		(40.1)		(23.9)	(24.0)	(24.4)	(24.1)	(23.2)
Wetlands Remaining Wetlands	(7.4)		(6.5)		(8.0)	(8.0)	(8.0)	(8.0)	(8.0)
Land Converted to Wetlands	0.4		0.4		(0.1)	(+)	(+)	(+)	(+)
Settlements Remaining Settlements	(109.6)		(116.6)		(125.9)	(123.8)	(123.7)	(123.6)	(124.1)
Land Converted to Settlements	62.9		85.0		80.1	79.4	79.3	79.3	79.2
CH$_4$	**5.0**		**9.3**		**16.6**	**7.7**	**15.3**	**13.8**	**13.8**
Forest Land Remaining Forest Land: Forest Fires[b]	0.9		5.0		12.2	3.4	11.0	9.5	9.5
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.7		3.8		3.8	3.8	3.8	3.8	3.8
Grassland Remaining Grassland: Grassland Fires[c]	0.1		0.3		0.3	0.3	0.3	0.3	0.3
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.2		0.2		0.2	0.2	0.2	0.2	0.2
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+		+		+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+		+		+	+	+	+	+

[4] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

	3.0		7.5		11.3	5.5	10.6	9.7	9.7

N₂O — rendering as table below.

Category	1990		2005		2015	2016	2017	2018	2019
N₂O	**3.0**		**7.5**		**11.3**	**5.5**	**10.6**	**9.7**	**9.7**
Forest Land Remaining Forest Land: Forest Fires[b]	0.6		3.3		8.1	2.2	7.3	6.2	6.2
Settlements Remaining Settlements: Settlement Soils[e]	2.0		3.1		2.2	2.2	2.3	2.4	2.4
Forest Land Remaining Forest Land: Forest Soils[f]	0.1		0.5		0.5	0.5	0.5	0.5	0.5
Grassland Remaining Grassland: Grassland Fires[c]	0.1		0.3		0.3	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1		0.2		0.1	0.1	0.1	0.1	0.1
Forest Land Remaining Forest Land: Drained Organic Soils[d]	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+		+		+	+	+	+	+
LULUCF Carbon Stock Change[a]	**(908.7)**		**(804.8)**		**(791.7)**	**(856.0)**	**(792.0)**	**(824.9)**	**(812.7)**
LULUCF Emissions[g]	**7.9**		**16.8**		**27.8**	**13.2**	**26.0**	**23.4**	**23.5**
LULUCF Sector Net Total[h]	**(900.8)**		**(788.1)**		**(763.8)**	**(842.8)**	**(766.1)**	**(801.4)**	**(789.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.05 MMT CO₂ Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements.*

[b] Estimates include CH₄ and N₂O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH₄ and N₂O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland*.

[d] Estimates include CH₄ and N₂O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Estimates include N₂O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[f] Estimates include N₂O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[g] LULUCF emissions include the CH₄ and N₂O emissions reported for *Peatlands Remaining Peatlands*, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH₄ emissions from *Land Converted to Coastal Wetlands*; and N₂O emissions from Forest Soils and Settlement Soils.

[h] The LULUCF Sector Net Total is the net sum of all LULUCF CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes in units of MMT CO₂ Eq.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990		2005		2015	2016	2017	2018	2019
Carbon Stock Change (CO₂)[a]	**(908,722)**		**(804,823)**		**(791,695)**	**(855,998)**	**(792,046)**	**(824,885)**	**(812,695)**
Forest Land Remaining Forest Land	(787,559)		(661,530)		(671,413)	(721,870)	(659,737)	(698,628)	(691,782)
Land Converted to Forest Land	(98,170)		(98,673)		(98,943)	(99,005)	(99,075)	(99,079)	(99,080)
Cropland Remaining Cropland	(23,176)		(29,002)		(12,826)	(22,724)	(22,290)	(16,595)	(14,539)
Land Converted to Cropland	51,765		52,160		56,051	54,401	54,563	54,265	54,225
Grassland Remaining Grassland	8,315		10,024		13,149	9,754	11,278	11,686	14,506
Land Converted to Grassland	(6,248)		(40,081)		(23,927)	(24,023)	(24,396)	(24,149)	(23,165)
Wetlands Remaining Wetlands	(7,399)		(6,549)		(8,021)	(8,046)	(7,954)	(7,991)	(8,011)
Land Converted to Wetlands	449		439		(56)	(47)	(38)	(28)	(19)
Settlements Remaining	(109,567)		(116,642)		(125,854)	(123,790)	(123,707)	(123,638)	(124,062)

Settlements Land Converted to Settlements	62,867	85,032	80,145	79,350	79,310	79,271	79,233
CH₄	**198**	**372**	**663**	**308**	**614**	**552**	**552**
Forest Land Remaining Forest Land: Forest Fires[b]	35	198	489	135	440	379	379
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	152	153	153	153	153
Grassland Remaining Grassland: Grassland Fires[c]	3	13	13	11	12	12	12
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	8	8	8	7	7
Forest Land Remaining Forest Land: Drained Organic Soils[d]	1	1	1	1	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	**10**	**25**	**38**	**18**	**36**	**32**	**32**
Forest Land Remaining Forest Land: Forest Fires[b]	2	11	27	7	24	21	21
Settlements Remaining Settlements: Settlement Soils[e]	7	10	7	8	8	8	8
Forest Land Remaining Forest Land: Forest Soils[f]	+	2	2	2	2	2	2
Grassland Remaining Grassland: Grassland Fires[c]	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	+	+	+	+	+
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+	+	+	+	+	+	+
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Wetlands Remaining Wetlands, Land Converted to Wetlands, Settlements Remaining Settlements,* and *Land Converted to Settlements*.

[b] Estimates include CH₄ and N₂O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH₄ and N₂O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland*.

[d] Estimates include CH₄ and N₂O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[e] Estimates include N₂O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

[f] Estimates include N₂O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Each year, some emission and sink estimates in the LULUCF sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate. Of the updates implemented, the most significant include (1) Forest Lands: use

of new data from the National Forest Inventory (NFI), compiling population estimates of carbon stocks and stock changes using NFI data from each U.S. state and summing over all states to obtain the national estimates, refined estimates in the Digital General Soil Map, and new data on area burned from the Monitoring Trends in Burn Severity (MTBS) data product; and (2) Coastal Wetlands: including belowground biomass carbon stock changes, and use of new data from the Coastal Change Analysis Program (C-CAP), the USDA's Soil Survey Geographic Database (SSURGO) and fisheries data from NOAA. Together, these updates for 2018 increased total sequestration of CO_2 by 25.0 MMT CO_2 Eq. (3 percent) and decreased total non-CO_2 emissions by 2.7 MMT CO_2 Eq. (10 percent), compared to the previous Inventory (i.e., 1990 to 2018). For more information on specific methodological updates, please see the Recalculations discussion within the respective source category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states, however, for Hawaii and Alaska some land use and land use changes are not included (see chapter sections on "Uncertainty and Time-Series Consistency" and "Planned Improvements" for more details). In addition, U.S. Territories are not included. EPA continues to review available data on an ongoing basis to include emissions from territories and DC in a future inventories to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this Inventory.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and the *2013 Supplement*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[5] The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations, but rather, this Chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land-use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed

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[5] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (See IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land-use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[6] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[7] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[8]

The total land area included in the United States Inventory is 936 million hectares across the 50 states.[9] Approximately 886 million hectares of this land base is considered managed and 50 million hectares is unmanaged, which has not changed much over the time series of the Inventory (Table 6-5). In 2019, the United States had a total of 282 million hectares of managed Forest Land (0.03 percent decrease compared to 1990). There are 162 million hectares of cropland (7.2 percent decrease compared to 1990), 337 million hectares of managed Grassland (0.01 percent increase compared to 1990), 39 million hectares of managed Wetlands (1.8 percent increase compared to 1990), 45 million hectares of Settlements (34 percent increase compared to 1990), and 22 million hectares of managed Other Land (2.4 percent increase compared to 1990) (Table 6-5).

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are reported mostly as managed.[10] In addition, C stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (e.g., *Grassland Remaining Grassland* within interior Alaska).[11,12] There are also discrepancies in the inventory emissions data and the land representation section because new FIA data were used in the inventory analysis, but were not incorporated into the land representation analysis due to timing of data availability and resources to complete the analysis. The land representation analysis will incorporate the new time series of FIA data int the next Inventory. In addition, planned improvements are under development to estimate C stock changes and greenhouse gas emissions on all managed land and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

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[6] NRI data are available at <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/>.

[7] FIA data are available at <http://www.fia.fs.fed.us/tools-data/default.asp>.

[8] NLCD data are available at <http://www.mrlc.gov/> and MRLC is a consortium of several U.S. government agencies.

[9] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future Inventories. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

[10] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all Wetlands in the conterminous United States and Hawaii are reported as managed. See the Planned Improvements section of the Inventory for future refinements to the Wetland area estimates.

[11] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in the next Inventory.

[12] These "managed area" discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns (Figure 6-3). Forest Land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2015	2016	2017	2018	2019[a]
Managed Lands	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**
Forest	281,621	281,681	281,945	281,796	281,652	281,546	281,546
Croplands	174,471	165,727	161,929	161,933	161,933	161,933	161,933
Grasslands	336,840	337,621	336,529	336,657	336,781	336,863	336,863
Settlements	33,446	40,469	44,799	44,795	44,797	44,797	44,797
Wetlands	38,422	39,017	39,076	39,089	39,108	39,132	39,132
Other	21,715	21,997	22,236	22,243	22,243	22,243	22,243
Unmanaged Lands	**49,681**	**49,684**	**49,683**	**49,683**	**49,683**	**49,683**	**49,683**
Forest	9,243	8,829	8,208	8,208	8,208	8,208	8,208
Croplands	0	0	0	0	0	0	0
Grasslands	25,530	25,962	26,608	26,608	26,608	26,608	26,608
Settlements	0	0	0	0	0	0	0
Wetlands	4,166	4,166	4,165	4,165	4,165	4,165	4,165
Other	10,742	10,727	10,701	10,701	10,701	10,701	10,701
Total Land Areas	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**
Forest	290,864	290,510	290,153	290,004	289,860	289,754	289,754
Croplands	174,471	165,727	161,929	161,933	161,933	161,933	161,933
Grasslands	362,370	363,583	363,138	363,266	363,389	363,471	363,471
Settlements	33,446	40,469	44,799	44,795	44,797	44,797	44,797
Wetlands	42,589	43,183	43,241	43,254	43,273	43,297	43,297
Other	32,457	32,725	32,937	32,944	32,944	32,944	32,944

[a] Land use data were not updated in this Inventory and the data for 2019 were assumed to be the same as in 2018. New land use activity data will be incorporated and the time series will be updated in the next Inventory.

Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land-Use & Land-Use Change Categories[a]	1990	2005	2015	2016	2017	2018	2019[b]
Total Forest Land	**281,621**	**281,681**	**281,945**	**281,796**	**281,652**	**281,546**	**281,546**
FF	280,393	280,207	280,528	280,529	280,380	280,274	280,274
CF	169	167	139	134	135	135	135
GF	919	1,162	1,125	989	992	992	992
WF	77	28	25	25	25	25	25
SF	12	24	27	26	26	26	26
OF	50	93	100	93	93	93	93
Total Cropland	**174,471**	**165,727**	**161,929**	**161,933**	**161,933**	**161,933**	**161,933**
CC	162,163	150,304	148,880	148,885	148,884	148,884	148,884
FC	182	86	58	58	58	58	58
GC	11,738	14,820	12,609	12,609	12,609	12,609	12,609
WC	118	178	104	104	104	104	104
SC	75	100	99	99	99	99	99
OC	195	239	179	179	179	179	179
Total Grassland	**336,840**	**337,621**	**336,529**	**336,657**	**336,781**	**336,863**	**336,863**

GG	327,446	315,161	316,287	316,408	316,502	316,622	316,622
FG	593	560	547	553	583	545	545
CG	8,237	17,523	16,600	16,600	16,600	16,600	16,600
WG	176	542	308	308	308	308	308
SG	43	509	346	346	346	346	346
OG	345	3,328	2,442	2,442	2,442	2,442	2,442
Total Wetlands	**38,422**	**39,017**	**39,076**	**39,089**	**39,108**	**39,132**	**39,132**
WW	37,860	37,035	37,602	37,616	37,634	37,658	37,658
FW	83	59	54	54	54	54	54
CW	132	566	440	440	440	440	440
GW	297	1,187	836	836	836	836	836
SW	0	38	25	25	25	25	25
OW	50	133	118	118	118	118	118
Total Settlements	**33,446**	**40,469**	**44,799**	**44,795**	**44,797**	**44,797**	**44,797**
SS	30,585	31,522	38,210	38,210	38,210	38,210	38,210
FS	310	549	544	539	541	541	541
CS	1,237	3,602	2,452	2,452	2,452	2,452	2,452
GS	1,255	4,499	3,352	3,352	3,352	3,352	3,352
WS	4	61	46	46	46	46	46
OS	54	235	197	197	197	197	197
Total Other Land	**21,715**	**21,997**	**22,236**	**22,243**	**22,243**	**22,243**	**22,243**
OO	20,953	18,231	19,000	19,007	19,007	19,007	19,007
FO	41	70	90	90	90	90	90
CO	301	590	678	678	678	678	678
GO	391	2,965	2,331	2,331	2,331	2,331	2,331
WO	26	121	121	121	121	121	121
SO	2	20	16	16	16	16	16
Grand Total	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for Wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include territories in future Inventories. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (see land use chapters e.g., *Forest Land Remaining Forest Land* for more information). Totals may not sum due to independent rounding.

[a] The abbreviations are "F" for Forest Land, "C" for Cropland, "G" for Grassland, "W" for Wetlands, "S" for Settlements, and "O" for Other Lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is *Forest Land Remaining Forest Land*), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is *Cropland Converted to Forest Land*).

[b] Land use data were not updated in this Inventory and the data for 2019 were assumed to be the same as in 2018. New land use activity data will be incorporated and the time series will be updated in the next Inventory.

Figure 6-3: Percent of Total Land Area for Each State in the General Land-Use Categories for 2019

Forest Lands

Croplands

Grasslands

Wetlands

Settlements

Other Lands
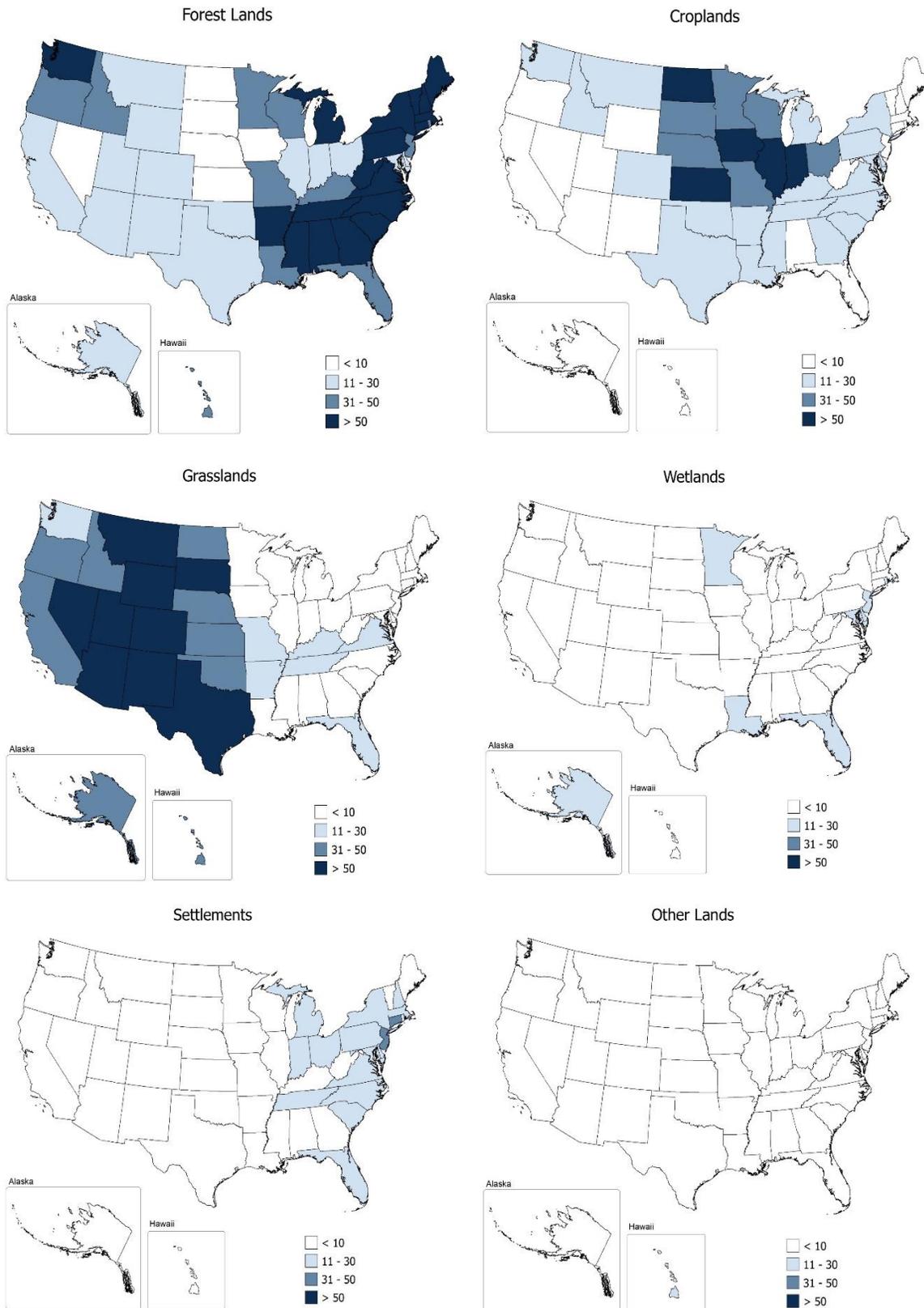
Methodology

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps derived from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[13]

- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

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[13] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions and peatlands due to insufficient activity data to estimate emissions and limited resources to improve the inventory. See the Planned Improvements section of the Inventory for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[14]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on C stocks. Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[15] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[16] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest Land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest Land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as Forest Land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for Forest Land. These areas are classified as Settlements. In addition, Forest Land does not include land that is predominantly under an agricultural land use (Oswalt et al. 2014).

- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[17] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for Forest Land. Lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[18]) are also classified as Cropland, as long as these areas do not meet the Forest Land criteria. Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.

- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both

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[14] There are some areas, such as Forest Land and Grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[15] See <http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2015/Core-FIA-FG-7.pdf>, page 22.

[16] See <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/>.

[17] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the Cropland land base.

[18] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as Grassland if there have been three or fewer years of continuous hay production.[19] Savannas, deserts, and tundra are considered Grassland.[20] Drained wetlands are considered Grassland if the dominant vegetation meets the plant cover criteria for Grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in Croplands (e.g., rice cultivation and cranberry production), Grasslands (e.g., wet meadows dominated by grass cover) and Forest Lands (e.g., Riparian Forests near waterways).

- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of Forest Land, and tracts of less than 10 acres (4.05 ha) that may meet the definitions for Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the Settlements category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.

- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), C stock changes and non-CO_2 emissions are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools. However, C stock changes and non-CO_2 emissions are estimated for *Land Converted to Other Land* during the first 20 years following conversion to account for legacy effects.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main sources for land-use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate C stock changes, N_2O, and CH_4 emissions on those

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[19] Areas with four or more years of continuous hay production are Cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

[20] *2006 IPCC Guidelines* do not include provisions to separate desert and tundra as land-use categories.

lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

	NRI	FIA	NLCD
Forest Land			
Conterminous United States			
Non-Federal		•	
Federal		•	
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal		•	•
Federal		•	•
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
Non-Federal	•		
Federal			•
Hawaii			
Non-Federal	•		
Federal			•
Alaska			
Non-Federal			•
Federal			•

National Resources Inventory

For the Inventory, the NRI is the official source of data for land use and land use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for Croplands and Grasslands (i.e., agricultural lands), and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (Note: most of the data has the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land-use data for non-federal lands in the conterminous United States and Hawaii. This Inventory incorporates data through 2015 from the NRI. The land use patterns are assumed to remain the same from 2016 through 2019 for this Inventory, but the time series will be updated when new data are released.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory and is another statistically-based survey for the conterminous United States in addition to the including southeast and south-central coastal Alaska. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest-land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for Forest Land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to 14 years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2015 through 2018; see Table A-203 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. In addition, FIA only records data for forest land across the land base in the conterminous United States and Alaska.[21] Consequently, gaps exist in the land representation when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of Forest Lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, and 2016 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015), and also for Alaska in 2001 and 2011 and Hawaii in 2001. A Land Cover Change Product is also available for Alaska from 2001 to 2011. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land use patterns are assumed to remain the same after the last year of data in the time series, which is 2001 for Hawaii, 2016 for the conterminous United States and 2011 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories derived from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

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[21] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land, Wetlands or Other Lands may be designated as unmanaged land;[23]
- All Forest Lands with active fire protection are considered managed;
- All Forest Lands designated for timber harvests are considered managed;
- All Grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged, remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest Lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data do lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance. Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged

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[23] All wetlands are considered managed in this Inventory with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land-use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for Forest Land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the Forest Land among the three databases. NRI and FIA have different criteria for classifying Forest Land in addition to different sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Any change in Forest Land Area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the Forest Land area and the amount of land designated as other land uses, such as the amount of Grassland, Cropland, and Wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. Adjustments are made in the *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, and Forest Land converted to other uses (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with Forest Land and conversions to and from Forest Land. There are three steps in this process. The first step involves adjustments to *Land Converted to Forest Land* (Grassland, Cropland, Settlements, Other Lands, and Wetlands), followed by a second step in which there are adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands), and finally the last step is to adjust *Forest Land Remaining Forest Land*.

In the first step, *Land Converted to Forest Land* in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal *Land Converted to Forest Land*, respectively. FIA data have not provided specific land-use categories that are converted to Forest Land in the past, but rather a sum of all *Land Converted to Forest Land*.[26] The NRI and NLCD provide information on specific land use conversions, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land use conversions into Forest Land for the state, prior to any adjustments. For example, if 50 percent of the land use change to Forest Land is associated with *Grassland Converted to Forest Land* in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of *Land Converted to Forest Land* is addressed by increasing or decreasing the area in *Grassland Converted to Forest Land*. Moreover, any increase or decrease in *Grassland Converted to Forest Land* in NRI or NLCD is addressed by a corresponding change in the area of *Grassland Remaining Grassland*, so that the total amount of managed area is not changed within an individual state.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for Forest Land converted to other uses. Similar to *Land Converted to Forest Land*, FIA have not provided information

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[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base derived from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

[26] The FIA program has started to collect data on the specific land uses that are converted to Forest Land, which will be further investigated and incorporated into a future Inventory.

on the specific land-use changes in the past,[27] and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets.

In the final step, the area of *Forest Land Remaining Forest Land* in a given state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in *Forest Land Remaining Forest Land* is associated with an under- or over-prediction of *Grassland Remaining Grassland* and *Wetland Remaining Wetland* in the NRI and NLCD. This step also assumes that there are no changes in the land use conversion categories. Therefore, corresponding increases or decreases are made in the area estimates of *Grasslands Remaining Grasslands* and *Wetlands Remaining Wetlands* from the NRI and NLCD. This adjustment balances the change in *Forest Land Remaining Forest Land* area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

The modified NRI data are then aggregated to provide the land-use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land in the conterminous United States and Alaska. FIA does have survey plots in Alaska that are used to determine the C stock changes, and the associated area data for this region are harmonized with the NLCD using the methods described above. NRI is used in the current report to provide Forest Land areas on non-federal lands in Hawaii, and NLCD is used for federal lands. FIA data is being collected in Hawaii and U.S. Territories, however there is insufficient data to make population estimates for this Inventory.

- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD is used to determine Cropland area and soil C stock changes on federal lands in the conterminous United States and Hawaii. NLCD is also used to determine croplands in Alaska, but C stock changes are not estimated for this region in the current Inventory.

- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and non-CO_2 greenhouse emissions on Grassland. Grassland area and soil C stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current Inventory does not include C stock changes in these areas.

- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]

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[27] The FIA program has started to collect data on specific land uses following conversion from Forest Land, which will be further investigated and incorporated into a future Inventory.

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acres (4.05 ha) threshold and are Grassland, they are classified as Grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.

- *Other Land*: Any land that is not classified into one of the previous five land-use categories, is categorized as Other Land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may also meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as Cropland if they are used for crop production, such as rice, or as Grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the Inventory if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy, and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land use change. Regardless, the Census does provide sufficient information to provide a check on the Inventory data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares derived from the combined NRI, FIA, and NLCD data. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4

percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

No recalculations were performed for the 1990 through 2018 portion of the time series, thus the land use areas for 2019 are assumed the same as 2018.

Planned Improvements

The next (i.e., 1990 through 2020) Inventory will be improved by using new NRI, FIA and possibly NLCD data to update the time series for land representation, providing consistency between the total area of managed land in the land representation section and the remainder of the Inventory. Another key planned improvement for the Inventory is to fully incorporate area data by land-use type for U.S. Territories. Fortunately, most of the managed land in the United States is included in the current land-use data, but a complete reporting of all lands in the United States is a key goal for the near future. Preliminary land-use area data for U.S. Territories by land-use category are provided in Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national Inventory as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the Inventory. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico so the NLCD was used for this area. The final selection of land-cover products for these territories is still under discussion. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land-Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas

emissions from coastal wetlands have been developed for the Inventory using the NOAA C-CAP land cover product. The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for the next (i.e., 1990 through 2020) Inventory is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. In addition, the current Inventory does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRF Category 4A1)

Changes in Forest Carbon Stocks (CRF Category 4A1)

Delineation of Carbon Pools

For estimating carbon (C) stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.

- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.

- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.

- Litter, which includes all duff, humus, and fine woody debris above the mineral soil and includes woody fragments with diameters of up to 7.5 cm.

- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

In addition, there are two harvested wood pools included when estimating C flux:

- Harvested wood products (HWP) in use.

- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined C storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and is also transferred to the litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate

of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest C stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later, or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in C stocks in the five C storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining C stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states and Alaska and inventories have been initiated in Hawaii and some of the U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the C estimates (Domke et al. 2016; Domke et al. 2017). First, the total C stocks are estimated for each C storage pool at the individual NFI plot, next the annual net changes in C stocks for each pool are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in C stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (See Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the C stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years. The methods and data used to delineate forest C stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of modeling approaches for carbon estimation were used in this Inventory.

Forest Area in the United States

Approximately 32 percent of the U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section Representation of the U.S. Land Base. All annual NFI plots included in the public FIA database as of August 2020 (which includes data collected through 2019) were used in this Inventory. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. The NFIs from each of the conterminous 48 states (CONUS; USDA Forest Service 2020a, 2020b) and Alaska comprise an estimated 279 million hectares of forest land that are considered managed and are included in the current Inventory. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual NFI data through 2019 for all states (USDA Forest Service 2020b, Nelson et al. 2020). Sufficient annual NFI data are not yet available for Hawaii and the U.S. Territories to include them in them in this section of the Inventory but estimates of these areas are included in Oswalt et al. (2019). While Hawaii and U.S. Territories have relatively small areas of forest land and thus may not substantially influence the overall C budget for forest land, these regions will be added to the forest C estimates as sufficient data become available. Since HI was not included in this section of the current Inventory there are small differences in the area estimates reported in this section and those reported in Section 6 Representation of the

U.S. Land Base.[29] Agroforestry systems that meet the definition of forest land are also not currently included in the current Inventory since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI)[30] of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, and Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than the forest land removed from production because it does not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019) with the southern region of the United States containing the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the CONUS and Alaska represented here is stable but there are substantial conversions as described in Section 6 Representation of the U.S. Land Base and each of the land conversion sections for each land use category (e.g., *Land Converted to Cropland*, *Land Converted to Grassland*). The major influences on the net C flux from forest land across the 1990 to 2019 time series are management activities, natural disturbance, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other C storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C in the aboveground biomass pool.[31] Though harvesting forests removes much of the C in aboveground biomass (and possibly changes C density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is about double the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in *Forest Land Remaining Forest Land* are captured in the estimates of C stocks and fluxes presented in this section.

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[29] See Annex 3.13, Table A-214 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

[30] The Natural Resources Inventory of the USDA Natural Resources Conservation Service is described in Section 6 Representation of the U.S. Land Base.

[31] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. A carbon fraction of 0.5 is used to convert dry biomass to C (USDA Forest Service 2020d).

Figure 6-4: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and Alaska (1990-2019)
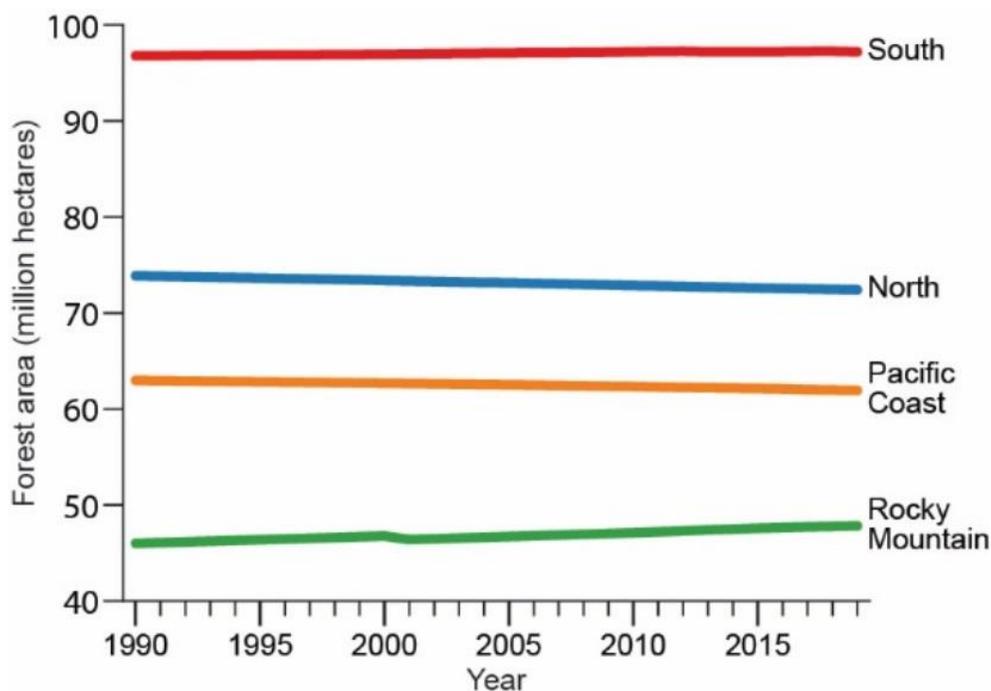
Forest Carbon Stocks and Stock Change

In *Forest Land Remaining Forest Land*, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net uptake (i.e., net sequestration or accumulation) of C each year from 1990 through 2019. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net C fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). Maintaining current harvesting practices and regeneration activities on these forested lands, along with continued input of harvested products into the HWP pool, C stocks in the *Forest Land Remaining Forest Land* category are likely to continue to increase in the near term, though possibly at a lower rate. Changes in

C stocks in the forest ecosystem and harvested wood pools associated with *Forest Land Remaining Forest Land* were estimated to result in net uptake of 691.8 MMT CO_2 Eq. (188.7 MMT C) in 2019 (Table 6-8, Table 6-9, Table A-211, A-212 and state-level estimates in A-215). The estimated net uptake of C in the Forest Ecosystem was 583.3 MMT CO_2 Eq. (159.1 MMT C) in 2019 (Table 6-8 and Table 6-9). The majority of this uptake in 2019, 394.0 MMT CO_2 Eq. (107.4 MMT C), was from aboveground biomass. Overall, estimates of average C density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 191 MT C ha^{-1} from 1990 to 2019. This was calculated by dividing the Forest Land area estimates by Forest Ecosystem C Stock estimates for every year (see Table 6-10 and Table A-213) and then calculating the mean across the entire time series, i.e., 1990 through 2019. The increasing forest ecosystem C density when combined with relatively stable forest area results in net C accumulation over time. Aboveground live biomass is responsible for the majority of net C uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in C density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series and much of this variability can be attributed to severe fire years. The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the CONUS. In Alaska, more than 12 percent of forest ecosystem C is stored in the litter carbon pool whereas in the CONUS only 6 percent of the total ecosystem C stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) which is why there are substantial C losses in this pool during severe fire years (Figure 6-5, A-229).

The estimated net uptake of C in HWP was 108.5 MMT CO_2 Eq. (29.6 MMT C) in 2019 (Table 6-8,Table 6-9, Table A-211, and A-212). The majority of this uptake, 69.3 MMT CO_2 Eq. (18.9 MMT C), was from wood and paper in SWDS. Products in use were an estimated 39.2 MMT CO_2 Eq. (10.7 MMT C) in 2019.

Table 6-8: Net CO$_2$ Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO$_2$ Eq.)

Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Forest Ecosystem	**(663.8)**	**(555.5)**	**(582.7)**	**(629.5)**	**(564.0)**	**(599.8)**	**(583.3)**
Aboveground Biomass	(456.4)	(401.3)	(414.2)	(421.3)	(395.1)	(402.4)	(394.0)
Belowground Biomass	(103.7)	(92.0)	(92.6)	(95.0)	(89.2)	(90.9)	(89.2)
Dead Wood	(97.3)	(93.5)	(98.7)	(105.1)	(97.1)	(101.7)	(99.3)
Litter	(8.1)	32.2	30.5	(3.2)	0.2	(2.3)	(0.5)
Soil (Mineral)	1.5	(1.5)	(7.3)	(6.8)	14.3	(4.5)	(2.4)
Soil (Organic)	(0.6)	(0.2)	(1.1)	1.2	2.1	1.2	1.2
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(88.7)**	**(92.4)**	**(95.7)**	**(98.8)**	**(108.5)**
Products in Use	(54.8)	(42.6)	(24.6)	(27.8)	(30.3)	(31.5)	(39.2)
SWDS	(69.0)	(63.4)	(64.1)	(64.6)	(65.5)	(67.2)	(69.3)
Total Net Flux	**(787.6)**	**(661.5)**	**(671.4)**	**(721.9)**	**(659.7)**	**(698.6)**	**(691.8)**

Notes: Forest ecosystem C stock changes do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6. See Annex 3.13, Table A-214 for annual differences between the forest area

reported in Section 6 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-20 and Table 6-21 for non-CO_2 emissions from drainage of organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Table 6-9: Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Forest Ecosystem	**(181.0)**	**(151.5)**	**(158.9)**	**(171.7)**	**(153.8)**	**(163.6)**	**(159.1)**
Aboveground Biomass	(124.5)	(109.5)	(113.0)	(114.9)	(107.7)	(109.7)	(107.4)
Belowground Biomass	(28.3)	(25.1)	(25.3)	(25.9)	(24.3)	(24.8)	(24.3)
Dead Wood	(26.5)	(25.5)	(26.9)	(28.7)	(26.5)	(27.7)	(27.1)
Litter	(2.2)	8.8	8.3	(0.9)	0.1	(0.6)	(0.1)
Soil (Mineral)	0.4	(0.4)	(2.0)	(1.9)	3.9	(1.2)	(0.7)
Soil (Organic)	(0.2)	(0.1)	(0.3)	0.3	0.6	0.3	0.3
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(24.2)**	**(25.2)**	**(26.1)**	**(26.9)**	**(29.6)**
Products in Use	(14.9)	(11.6)	(6.7)	(7.6)	(8.3)	(8.6)	(10.7)
SWDS	(18.8)	(17.3)	(17.5)	(17.6)	(17.9)	(18.3)	(18.9)
Total Net Flux	**(214.8)**	**(180.4)**	**(183.1)**	**(196.9)**	**(179.9)**	**(190.5)**	**(188.7)**

Notes: Forest ecosystem C stock changes do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in 6 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6. See Annex 3.13, Table A-214 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

[a] These estimates include carbon stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the C flux from drained organic soils. Also, see Table 6-20 and Table 6-21 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Stock estimates for forest ecosystem and harvested wood C storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil C pools account for a large proportion of total forest ecosystem C stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6 Representation of the U.S. Land Base for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-10 only include managed forest land in the conterminous 48 states and Alaska while the area estimates in Section 6 include all managed forest land in Hawaii. Differences also exist because forest land area estimates are based on the latest NFI data through 2019 and woodland areas previously included as forest land have been separated and included in the Grassland categories in this Inventory.[32]

Table 6-10: Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Forest Area (1,000 ha)	*279,661*	*279,491*	*279,533*	*279,511*	*279,483*	*279,386*	*279,289*
Carbon Pools (MMT C)							
Forest Ecosystem	**50,913**	**53,489**	**55,284**	**55,456**	**55,610**	**55,774**	**55,933**
Aboveground Biomass	11,810	13,584	14,820	14,935	15,043	15,152	15,260
Belowground Biomass	2,319	2,723	3,004	3,030	3,054	3,079	3,103
Dead Wood	2,049	2,446	2,743	2,771	2,798	2,825	2,852
Litter	3,656	3,655	3,636	3,637	3,637	3,638	3,638
Soil (Mineral)	25,145	25,145	25,147	25,149	25,145	25,146	25,147
Soil (Organic)	5,934	5,936	5,935	5,934	5,934	5,933	5,933
Harvested Wood	**1,895**	**2,353**	**2,591**	**2,616**	**2,642**	**2,669**	**2,699**
Products in Use	1,249	1,447	1,497	1,505	1,513	1,521	1,532
SWDS	646	906	1,094	1,112	1,129	1,148	1,167
Total C Stock	**52,808**	**55,842**	**57,875**	**58,072**	**58,252**	**58,443**	**58,632**

Notes: Forest area and C stock estimates include all *Forest Land Remaining Forest Land* in the conterminous 48 states and Alaska. Forest ecosystem C stocks do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stocks do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6. See Annex 3.13, Table A-214 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2019 requires estimates of C stocks for 2019 and 2020.

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[32] See Annex 3.13, Table A-214 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in C Stocks for All C Pools in *Forest Land Remaining Forest Land* in the Conterminous U.S. and Alaska (1990-2019)

Legend:
- All forest ecosystem pools
- Aboveground biomass
- Belowground biomass
- Dead wood
- Litter
- Soil (mineral)
- Soil (organic)
- Drained Organic Soil
- Harvested Wood Products (HWP)
- Products in use
- Solid waste disposal sites
- Total net change (forest ecosystem + HWP)
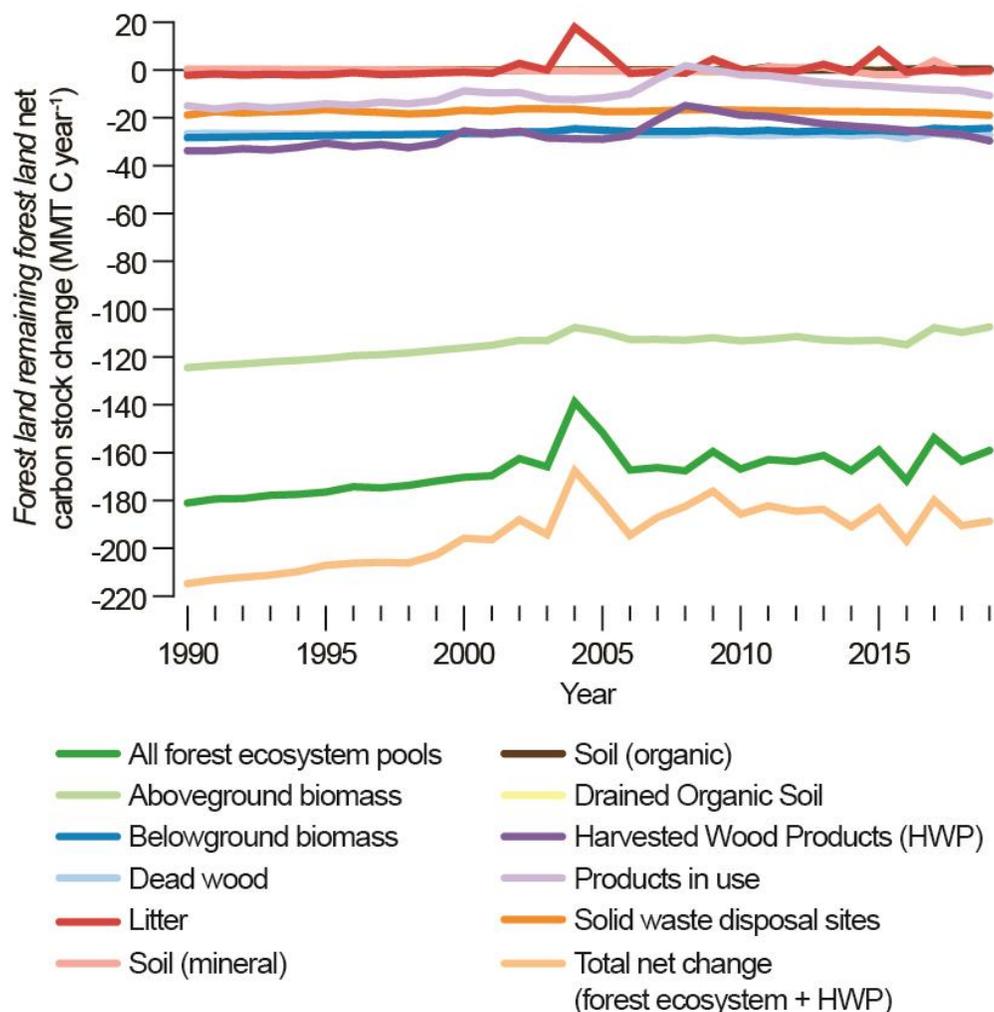
Box 6-3: CO₂ Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all C losses due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and UNFCCC reporting requirements.

The IPCC (2006) methodology with U.S.-specific data on annual area burned, potential fuel availability, and fire-specific severity and combustion were combined with IPCC default factors as needed to estimate CO_2 emissions from forest fires. The latest information on area burned is used to compile fire emissions for the United States. At the time this Inventory was compiled data were limited for 2018 and data for 2019 fires were unavailable;

therefore 2017 or 2018, the most recent available estimate, is applied to 2019. The 2019 estimates will be updated in subsequent reports as fire data become available. Estimated CO_2 emissions for wildfires in the conterminous 48 states and in Alaska as well as prescribed fires in 2019 were 126 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest C stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimate CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with C stock change estimates provided above.

Table 6-11: Estimates of CO₂ (MMT per Year) Emissions from Forest Fires in the Conterminous 48 States and Alaska[a]

Year	CO₂ emitted from Wildfires in the Conterminous 48 States (MMT yr⁻¹)	CO₂ emitted from Wildfires in Alaska(MMTyr⁻¹)	CO₂ emitted from Prescribed Fires (MMTyr⁻¹)	Total CO₂ emitted (MMTyr⁻¹)
1990	6.2	5.3	0.2	**11.7**
2005	20.5	44.1	1.5	**66.2**
2015	116.4	40.7	6.1	**163.2**
2016	33.7	1.7	9.7	**45.2**
2017	137.2	1.5	8.4	**147.1**
2018	115.5	2.9	8.0	**126.4**
2019[b]	115.5	2.9	8.0	**126.4**

Note: Totals may not sum due to independent rounding.

[a] These emissions have already been included in the estimates of net annual changes in C stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

[b] Some fire data for 2018 and all of 2019 were unavailable when these estimates were summarized; therefore 2017 or 2018, the most recent available estimate, is applied to 2019.

Methodology

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate C stocks and net annual C stock changes in Alaska. The approaches for estimating carbon stocks and stock changes on *Forest Land Remaining Forest Land* are described in Annex 3.13. All annual NFI plots available in the public FIA database (USDA Forest Service 2020b) were used in the current Inventory. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this report as were plots established and measured in 2015 and 2016 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6 Representation of the U.S. Land Base) are measured in the NFI, as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ with the other land use categories where area estimates reported in the Land Representation were not updated (see Section 6.1 Representation of the U.S. Land Base) Further, HI was not included in this section of the current Inventory so that also contributes to small differences in the area

estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base (See Annex 3.13 for details on differences). To implement the stock-difference approach, forest Land conditions in the CONUS were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2019. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation. To implement the gain-loss approach in Alaska, forest land conditions in Alaska were observed on NFI plots from 2004 to 2017. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2019. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all base intensity NFI plot locations (representing approximately 2,403 ha) in coastal southeast and southcentral Alaska and for 1/5 intensity plots in interior Alaska (representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses by forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2019. To estimate C stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems within the conterminous states and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 and Domke et al. (In prep) for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current Inventory which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures and enables the delineation of forest C accumulation by forest growth, land use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest C to disturbances and delineates *Land Converted to Forest Land* from *Forest Land Remaining Forest Land*. As part of this development, C pool science will continue and will be expanded to improve the estimates of C stock transfers from forest land to other land uses and include techniques to better identify land use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2020a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; USDA Forest Service 2020d, 2020a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five-panel design, with 20 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically 10 percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample

intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual inventory datasets by state. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as "moving window" averages, which mean that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2020d). Forest C estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five C storage pools identified by IPCC (2006) and described above. All estimates were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2020b, 2020c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. If inventory plots included data on individual trees, aboveground and belowground (coarse roots) tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of tree volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total carbon stocks or stock changes across all forest ecosystem C pools each year.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models as described below. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Carbon in Forest Soil

Soil carbon is the largest terrestrial C sink with much of that C in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O'Neill et al. 2005). Observations of mineral and organic soil C on forest land from the FIA program and the International Soil

Carbon Monitoring Network were used to develop and implement a modeling approach that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil C to a depth of 100 cm from empirical measurements to a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil C stocks specific to forest land in the United States (Domke et al. 2017). This new approach allowed for separation of mineral and organic soils, also referred to as Histosols, in the *Forest Land Remaining Forest Land* category. Note that mineral and organic (i.e., undrained organic soils) soil C stock changes are reported to a depth of 100 cm for *Forest Land Remaining Forest Land* to remain consistent with past reporting in this category, however for consistency across land-use categories mineral (e.g., cropland, grassland, settlements) soil C is reported to a depth of 30 cm in Section 6.3 *Land Converted to Forest Land*. Estimates of C stock changes from organic soils shown in Table 6-8 and Table 6-9 include separately the emissions from drained organic forest soils, the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in the estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The C loss from harvest is reported in the Forest Ecosystem component of the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* sections and for information purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3).

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007, Howard and Jones 2016, Howard and Liang 2019). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-215 for state-level uncertainties). A Monte Carlo Stochastic Simulation of the methods described above, and probabilistic sampling of C conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2019 net annual change for forest C stocks was estimated to be between -766.6 and -618.3 MMT CO_2 Eq. around a central estimate of -691.8 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of -651.8 to -514.9 MMT CO_2 Eq. around a central estimate of -583.3 MMT CO_2 Eq. for forest ecosystems and -138.5 to -81.7 MMT CO_2 Eq. around a central estimate of -108.5 MMT CO_2 Eq. for HWP. An error in the code used to compile the components of forest ecosystem uncertainty was identified while aggregating estimates and uncertainties by individual state in this Inventory. The error has been corrected in Table 6-12 resulting in a reduction in the uncertainty range relative to the flux estimate for forest ecosystems and thus, total forest uncertainty.

Table 6-12: Quantitative Uncertainty Estimates for Net CO₂ Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (MMT CO₂ Eq. and Percent)

| Source | Gas | 2019 Flux Estimate (MMT CO₂ Eq.) | Uncertainty Range Relative to Flux Estimate | | | |
| | | | (MMT CO₂ Eq.) | | (%) | |
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO₂	(583.3)	(651.8)	(514.9)	-11.7%	11.7%
Harvested Wood Products[b]	CO₂	(108.5)	(138.5)	(81.7)	-27.7%	24.7%
Total Forest	**CO₂**	**(691.8)**	**(766.6)**	**(618.3)**	**-10.8%**	**10.6%**

Note: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2020d).

General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the C datasets, which include inventory variables such as areas and volumes, were compared to

standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2020b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from U.S. Census and USDA Forest Service surveys of production and trade and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007, Howard and Jones 2016, Howard and Liang 2019). Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

The methods used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes and HWPs from 1990 through 2019 are consistent with those used in the previous (1990 through 2018) Inventory. However, population estimates of carbon stocks and stock changes were compiled using NFI data from each U.S. state and national estimates were compiled by summing over all states. In past Inventories population estimates were compiled by 4 geographic regions (Figure 6-4) and summed over all regions to compile national estimates. This improvement in resolution resulted in minor changes in the estimates over the time series due to rounding. Also, the state-level disaggregation contributed to identifying an error in the compilation of the Alaska time series data resulting in a one-year misalignment in carbon stock changes for this state in comparison to the 1990 through 2018 Inventory. This error has been corrected resulting in differences in each year of the time series (i.e., 1990 to 2018), given the one-year misalignment, with substantial differences in major fire years in Alaska. New NFI data contributed to minor decreases in forest land area and stock changes, particularly in the Intermountain West region (Table 6-13). Soil carbon stocks decreased in the latest Inventory relative to the previous Inventory and this change can be attributed to refinements in the Digital General Soil Map of the United States (STATSGO2) dataset where soil orders may have changed in the updated data product (Table 6-13). This resulted in a structural change in the soil organic carbon estimates for mineral and organic soils across the entire time series (Table 6-8).

Table 6-13: Recalculations of Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	Previous Estimate Year 2019, 2020 Inventory	Current Estimate Year 2019, 2021 Inventory	Current Estimate Year 2020, 2021 Inventory
Forest Area (1000 ha)	*279,682*	*279,386*	*279,289*
Carbon Pools (MMT C)			
Forest	**56,051**	**55,774**	**55,933**
Aboveground Biomass	14,989	15,152	15,260
Belowground Biomass	3,081	3,079	3,103
Dead Wood	2,777	2,825	2,852
Litter	3,641	3,638	3,638

Soil (Mineral)	25,638	25,146	25,147
Soil (Organic)	5,926	5,933	5,933
Harvested Wood	**2,669**	**2,669**	**2,699**
Products in Use	1,521	1,521	1,532
SWDS	1,148	1,148	1,167
Total Stock	**58,720**	**58,443**	**58,632**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	Previous Estimate Year 2018, 2020 Inventory	Current Estimate Year 2018, 2021 Inventory	Current Estimate Year 2019, 2021 Inventory
Forest	**(153.9)**	**(163.6)**	**(159.1)**
Aboveground Biomass	(105.1)	(109.7)	(107.4)
Belowground Biomass	(24.2)	(24.8)	(24.3)
Dead Wood	(23.6)	(27.7)	(27.1)
Litter	(0.8)	(0.6)	(0.1)
Soil (Mineral)	(0.9)	(1.2)	(0.7)
Soil (Organic)	0.4	0.3	0.3
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(26.9)**	**(26.9)**	**(29.6)**
Products in Use	(8.6)	(8.6)	(10.7)
SWDS	(18.3)	(18.3)	(18.9)
Total Net Flux	**(180.9)**	**(190.5)**	**(188.7)**

Note: Totals may not sum due to independent rounding.

Planned Improvements

Reliable estimates of forest C stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual Inventory submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual C pool estimation, coordination with other land-use categories, and annual inventory data incorporation.

While this Inventory submission includes C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* and C stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the CONUS in the current Inventory for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land use categories in the current Inventory, research is underway to leverage all FIA data and auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI, but not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which will eliminate latency in population estimates from the NFI, improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for easier harmonization of NFI data with auxiliary data products. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open source code (e.g., R programming language) in concert with the public availability of the annual NFI (USDA Forest Service 2020b). Also, several FIA database processes are being institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches were used to estimate uncertainty associated with C stock changes in the *Forest Land Remaining Forest Land* category in this report.

There is research underway investigating more robust approaches to total uncertainty (Clough et al. 2016), which will be considered in future Inventory reports.

The modeling framework used to estimate downed dead wood within the dead wood C pool will be updated similar to the litter (Domke et al. 2016) and soil C pools (Domke et al. 2017). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized with the Inventory report.

The foundation of forest C estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2020b). With the exception of Wyoming and western Oklahoma, all other states in the CONUS now have sufficient annual NFI data to consistently estimate C stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in Alaska as part of the operational NFI and as more plots are added to the NFI they will be used to improve estimates for all managed forest land in Alaska. The methods used to include all managed forest land in Alaska will be used in the years ahead for Hawaii and U.S. Territories as forest C data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid not only the interior Alaska effort but the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) as this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land use category (e.g., woodlands, which fall into the grasslands land use category, and urban areas, which fall into the settlements land use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO$_2$ Emissions from Forest Fires

Emissions of non-CO$_2$ gases from forest fires were estimated using U.S.-specific data for annual area of forest burned, potential fuel availability, and fire severity as well as the default IPCC (2006) emissions and some combustion factors applied to the IPCC methodology. In 2019, emissions from this source were estimated to be 9.5 MMT CO$_2$ Eq. of CH$_4$ and 6.2 MMT CO$_2$ Eq. of N$_2$O (Table 6-15; kt units provided in Table 6-16). The estimates of non-CO$_2$ emissions from forest fires include wildfires and prescribed fires in the conterminous 48 states and all managed forest land in Alaska.

Table 6-15: Non-CO$_2$ Emissions from Forest Fires (MMT CO$_2$ Eq.)[a]

Gas	1990		2005		2015	2016	2017	2018	2019[b]
CH$_4$	0.9		5.0		12.2	3.4	11.0	9.5	9.5
N$_2$O	0.6		3.3		8.1	2.2	7.3	6.2	6.2
Total	**1.5**		**8.2**		**20.3**	**5.6**	**18.3**	**15.7**	**15.7**

Note: Totals may not sum due to independent rounding

[a] These estimates include Non-CO$_2$ Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Some fire data for 2018 and all of 2019 were unavailable when these estimates were summarized; therefore 2017 or 2018, the most recent available estimate, is applied to 2019.

Table 6-16: Non-CO$_2$ Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2015	2016	2017	2018	2019[b]
CH_4	35	198	489	135	440	379	379
N_2O	2	11	27	7	24	21	21
CO	800	4511	11136	3080	10036	8626	8626
NO_x	22	126	312	87	281	242	242

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Some fire data for 2018 and all of 2019 were unavailable when these estimates were summarized; therefore 2017 or 2018, the most recent available estimate, is applied to 2019.

Methodology

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated following IPCC (2006) methodology, which included a combination of U.S. specific data on area burned, potential fuel available for combustion, and estimates of combustion based on fire severity along with IPCC default combustion and emission factors. The estimates were calculated according to Equation 2.27 of IPCC (2006) (Volume 4, Chapter 2), which is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission Factor} \times 10^{-3}$$

where forest area burned is based on Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007 and 2015) and National Land Cover (NLCD, Homer et al. 2015) data. Fuel estimates are based on current C density estimates obtained from FIA plot data, combustion is partly a function of burn severity, and emission factors are from IPCC (2006, Volume 4, Chapter 2). See Annex 3.13 for further details.

Uncertainty and Time-Series Consistency

In order to quantify the uncertainties for non-CO_2 emissions from wildfires and prescribed burns, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainty based on the model and data applied for U.S. forest land. See IPCC (2006) and Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-17.

Table 6-17: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	9.5	7.9	11.2	-16%	18%
Non-CO_2 Emissions from Forest Fires	N_2O	6.2	5.5	7.1	-13%	14%

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2019) Inventory to compile estimates of non-CO_2 emissions from forest fires are consistent with those used in the previous 1990 through 2018 Inventory. The recalculations reflected updates to MTBS and NFI data. These recalculations resulted in a 16 percent decrease in total emissions for 2018 as compared to the previous Inventory.

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest area burned, potential fuel available, and combustion. The goal is to develop easy to apply models based on readily available data to characterize the site and fire for the over twenty thousand fires in the MTBS data. The results will be less reliant on wide regional values or IPCC defaults. Spatially relating potential fuel availability to more localized forest structure is the best example of this. An additional future consideration is to apply the forest inventory data to identify and quantify the likely small additional contribution of fires that are below the minimum size threshold for the MTBS data.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia [NH_3] and nitrogen oxide [NO_x], in addition to leaching and runoff of nitrates [NO_3], and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*[33] in 2019 were 0.3 MMT CO_2 Eq. (1 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2019 were 0.5 MMT CO_2 Eq. (2 kt) and have increased by 455 percent from 1990 to 2019. Total forest soil N_2O emissions are summarized in Table 6-18.

Table 6-18: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2014	2015	2016	2017	2018	2019
Direct N_2O Fluxes from Soils										
MMT CO_2 Eq.	0.1		0.3		0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	+		1		1	1	1	1	1	1

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[33] The N_2O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

Indirect N$_2$O Fluxes from Soils									
MMT CO$_2$ Eq.	+		0.1		0.1	0.1	0.1	0.1	0.1	0.1
kt N$_2$O	+		+		+	+	+	+	+	+
Total									
MMT CO$_2$ Eq.	**0.1**		**0.5**		**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N$_2$O	**+**		**2**		**2**	**2**	**2**	**2**	**2**	**2**

Note: Totals may not sum due to independent rounding. The N$_2$O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

+ Does not exceed 0.05 MMT CO$_2$ Eq. or 0.5 kt.

Methodology

The IPCC Tier 1 approach is used to estimate N$_2$O from soils within *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N$_2$O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2019, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area are multiplied by the portion of fertilized area to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2019, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N$_2$O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent to estimate the amount of volatilized N that is converted to N$_2$O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent to estimate the amount of leached/runoff N that is converted to N$_2$O off-site. The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N$_2$O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N$_2$O emissions is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and areas of forest land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic N fertilizers to forest are captured in this inventory, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils in the United States is included in the inventory for Agricultural Soil Management (Section 5.4) and *Settlements Remaining Settlements* (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2004 activity data are directly applied to the 2019 emission estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-19. Direct N_2O fluxes from soils in 2019 are estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2019. Indirect N_2O emissions in 2019 are 0.1 MMT CO_2 Eq. and have a range are between 0.02 and 0.4 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2019.

Table 6-19: Quantitative Uncertainty Estimates of N₂O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO₂ Eq.)		(%)	
Forest Land Remaining Forest Land			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct N₂O Fluxes from Soils	N₂O	0.3	0.1	1.1	-59%	+211%
Indirect N₂O Fluxes from Soils	N₂O	0.1	+	0.4	-86%	+238%

Note: Totals may not sum due to independent rounding

+ Does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data.

Recalculations Discussion

No recalculations were performed for the 1990 to 2018 estimates.

CO₂, CH₄, and N₂O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the

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[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

[35] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2020b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current Inventory. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2020b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2020c, d) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2019 are estimated as 0.1 MMT CO_2 Eq. per year (Table 6-20; kt units provided in Table 6-21).

The Tier 1 methodology provides methods to estimate C emission as CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-20: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990		2005		2015	2016	2017	2018	2019
CH_4	+		+		+	+	+	+	+
N_2O	0.1		0.1		0.1	0.1	0. 1	0.1	0.1
Total	**0.1**		**0.1**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

Note: Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.
[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*
[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Table 6-21: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990		2005		2015	2016	2017	2018	2019
CH_4	0.6		0.6		0.6	0.6	0.6	0.6	0.6
N_2O	+		+		+	+	+	+	+

+ Does not exceed 0.5 kt.
[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*
[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Methodology

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2020d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-22).

Table 6-22: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of C emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway–indirect, or off-site, emissions–is associated with dissolved organic carbon releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of dissolved organic carbon (DOC) from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway–emissions from (peat) fires on organic soils–assumes that the drained organic soils burn in a fire but not any wet organic soils. However, this Inventory currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current Inventory, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from

these drained soils in contrast to the very low emissions from wet organic soils. Calculations are according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Uncertainty and Time-Series Consistency

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-23). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this inventory, which results in minor changes in the less significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2019 from drained organic soils on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* were estimated to be between 0.004 and 0.236 MMT CO_2 Eq. around a central estimate of 0.106 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-23: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-70%	80%
N_2O	0.1	+	0.2	-100%	128%
Total	**0.1**	**+**	**0.2**	**-96%**	**122%**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic C from drainage waters may be double counted if soil C stock and change is based on sampling and this C is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the Wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the 1990 to 2018 estimates.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports are made available and new geospatial products become available.

6.3 Land Converted to Forest Land (CRF Source Category 4A2)

The C stock change estimates for *Land Converted to Forest Land* that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as *Forest Land Remaining Forest Land*. Estimates of C stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the *Land Converted to Forest Land* category of this Inventory.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout U.S. history. The 1970s and 1980s saw a resurgence of federally-sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., Cropland, Grassland, Wetlands, Settlements, and Other Lands) to Forest Land resulted in a fairly continuous net annual accretion of Forest Land area from over the time series at an average rate of 1.0 million ha year^{-1}.

Over the 20-year conversion period used in the *Land Converted to Forest Land* category, the conversion of cropland to forest land resulted in the largest source of C transfer and uptake, accounting for approximately 40 percent of the uptake annually. Estimated C uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of C from all forest pool stock changes in 2019 was -99.1 MMT CO_2 Eq. (-27.0 MMT C) (Table 6-24 and Table 6-25).

Mineral soil C stocks increase slightly over the time series for Land Converted to Forest Land. The small gains are associated with Cropland Converted to Forest Land, Settlements Converted to Forest Land, and Other Land Converted to Forest Land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil C. In contrast, Grassland Converted to Forest Land leads to a loss of soil C across the time series, which negates some of the gain in soil C with the other land use conversions. Managed pasture to Forest Land is the most common conversion. This conversion leads to a loss of soil C because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances C input to soils relative to typical forest management activities.

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[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversion to forest in Alaska and Hawaii were not included. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. See Annex 3.13, Table A-214 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.3 Land Converted to Forest Land.

Table 6-24: Net CO₂ Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT CO₂ Eq.)

Land Use/Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to Forest Land	**(39.8)**	**(39.7)**	**(39.7)**	**(39.8)**	**(39.8)**	**(39.8)**	**(39.8)**
Aboveground Biomass	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)
Belowground Biomass	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)
Dead Wood	(5.0)	(5.0)	(5.1)	(5.1)	(5.1)	(5.1)	(5.1)
Litter	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)
Mineral Soil	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Grassland Converted to Forest Land	**(10.3)**	**(10.3)**	**(10.4)**	**(10.4)**	**(10.5)**	**(10.5)**	**(10.5)**
Aboveground Biomass	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Belowground Biomass	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Dead Wood	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Litter	(3.8)	(3.9)	(3.9)	(4.0)	(4.0)	(4.0)	(4.0)
Mineral Soil	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Other Land Converted to Forest Land	**(10.2)**	**(10.8)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**
Aboveground Biomass	(4.7)	(4.7)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.4)	(1.4)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Litter	(2.6)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Mineral Soil	(0.6)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Settlements Converted to Forest Land	**(34.6)**	**(34.5)**	**(34.5)**	**(34.5)**	**(34.5)**	**(34.5)**	**(34.5)**
Aboveground Biomass	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)	(21.1)
Belowground Biomass	(4.1)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)
Dead Wood	(3.9)	(3.9)	(3.9)	(3.9)	(4.0)	(4.0)	(4.0)
Litter	(5.4)	(5.4)	(5.4)	(5.4)	(5.4)	(5.4)	(5.4)
Mineral Soil	(0.1)	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	+	+	+	+	+	+	+
Total Aboveground Biomass Flux	**(54.9)**	**(54.9)**	**(55.0)**	**(55.0)**	**(55.1)**	**(55.1)**	**(55.1)**
Total Belowground Biomass Flux	**(10.6)**	**(10.7)**	**(10.7)**	**(10.7)**	**(10.7)**	**(10.7)**	**(10.7)**
Total Dead Wood Flux	**(11.7)**	**(11.7)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Total Litter Flux	**(20.1)**	**(20.2)**	**(20.3)**	**(20.3)**	**(20.4)**	**(20.4)**	**(20.4)**
Total Mineral Soil Flux	**(0.8)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**
Total Flux	**(98.2)**	**(98.7)**	**(98.9)**	**(99.0)**	**(99.1)**	**(99.1)**	**(99.1)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the Forest Land Remaining Forest Land section because there is insufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is insufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-218 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for all organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

Table 6-25: Net C Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to Forest Land	**(10.9)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.9)**	**(10.9)**	**(10.9)**
Aboveground Biomass	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)
Belowground Biomass	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Dead Wood	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Litter	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)
Mineral Soil	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.9)**	**(2.9)**	**(2.9)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(1.0)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Mineral Soil	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.8)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soil	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.4)**	**(9.4)**	**(9.4)**	**(9.4)**	**(9.4)**	**(9.4)**	**(9.4)**
Aboveground Biomass	(5.8)	(5.8)	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)
Belowground Biomass	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Mineral Soil	+	+	+	+	+	+	+
Wetlands Converted to Forest Land	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	+	+	+	+	+	+	+
Total Aboveground Biomass Flux	**(15.0)**	**(15.0)**	**(15.0)**	**(15.0)**	**(15.0)**	**(15.0)**	**(15.0)**
Total Belowground Biomass Flux	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**
Total Dead Wood Flux	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Total Litter Flux	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.6)**	**(5.6)**	**(5.6)**
Total Mineral Soil Flux	**(0.2)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Total Flux	**(26.8)**	**(26.9)**	**(27.0)**	**(27.0)**	**(27.0)**	**(27.0)**	**(27.0)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the *Forest Land Remaining Forest Land* section because there is not sufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-218 for annual differences between the forest area reported in Section 6 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

+ Absolute value does not exceed 0.05 MMT C.

Methodology

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. National Forest Inventory data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools. Estimates for Aboveground and Belowground Biomass, Dead Wood and Litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2020b, 2020c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the *Land Converted to Forest Land* are consistent with those used for *Forest Land Remaining Forest Land*. For land use conversion, IPCC (2006) default biomass C stocks removed due to land use conversion from Croplands and Grasslands were used in the year of conversion on individual plots. All annual NFI plots available through May 2019 were used in this Inventory. Forest Land conditions were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2019. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, above- and belowground tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from Grassland and Cropland to Forest Land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on Grasslands and aboveground biomass on Croplands were subtracted from sequestration in the year of the conversion. For all other land use (i.e., Other Lands, Settlements, Wetlands) conversions to Forest Land no biomass loss data were available and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect

intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). See Annex 3.12 (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management) for more information about this method. Note that soil C in this Inventory is reported to a depth of 100 cm in the Forest Land Remaining Forest Land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006), as described in Annex 3.12. For consistency, the same methods are also used for land use conversions to Cropland, Grasslands and Settlements in this Inventory.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis placed bounds on the flux estimates for *Land Converted to Forest Land* through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool C stock changes were developed using the same methodologies as described in the *Forest Land Remaining Forest Land* section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference C stocks in certain conversion categories (i.e., *Cropland Converted to Forest Land* and *Grassland Converted to Forest Land*). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used for mineral soils and is described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-26 for each land conversion category and C pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil C pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all C stocks in *Land Converted to Forest Land* ranged from 11 percent below to 11 percent above the 2019 C stock change estimate of -99.1 MMT CO_2 Eq.

Table 6-26: Quantitative Uncertainty Estimates for Forest C Pool Stock Changes (MMT CO₂ Eq. per Year) in 2019 from *Land Converted to Forest Land* by Land Use Change

Land Use/Carbon Pool	2019 Flux Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Flux Range[a]	
		(MMT CO₂ Eq.)	(%)

		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	**(39.8)**	**(48.6)**	**(31.0)**	**-22%**	**22%**
Aboveground Biomass	(23.0)	(31.6)	(14.4)	-38%	37%
Belowground Biomass	(4.5)	(5.6)	(3.4)	-24%	24%
Dead Wood	(5.1)	(6.3)	(3.8)	-24%	24%
Litter	(7.0)	(8.1)	(6.0)	-15%	15%
Mineral Soils	(0.2)	(0.5)	0.1	-134%	134%
Grassland Converted to Forest Land	**(10.5)**	**(12.9)**	**(8.1)**	**23%**	**23%**
Aboveground Biomass	(4.8)	(6.2)	(3.4)	-29%	29%
Belowground Biomass	(1.0)	(1.3)	(0.7)	-29%	29%
Dead Wood	(1.0)	(1.1)	(0.8)	-16%	16%
Litter	(4.0)	(4.5)	(3.4)	-14%	14%
Mineral Soils	0.3	(0.1)	0.6	-135%	135%
Other Lands Converted to Forest Land	**(11.0)**	**(13.4)**	**(8.7)**	**-21%**	**21%**
Aboveground Biomass	(4.8)	(6.9)	(2.7)	-44%	44%
Belowground Biomass	(0.9)	(1.3)	(0.5)	-47%	47%
Dead Wood	(1.5)	(2.0)	(0.9)	-38%	38%
Litter	(2.7)	(3.4)	(2.1)	-23%	23%
Mineral Soils	(1.1)	(1.9)	(0.4)	-64%	64%
Settlements Converted to Forest Land	**(34.5)**	**(41.0)**	**(28.0)**	**-19%**	**19%**
Aboveground Biomass	(21.1)	(27.3)	(14.9)	-29%	29%
Belowground Biomass	(4.0)	(5.4)	(2.7)	-33%	33%
Dead Wood	(4.0)	(5.1)	(2.8)	-29%	29%
Litter	(5.4)	(6.3)	(4.5)	-17%	17%
Mineral Soils	(0.1)	(0.1)	(0.0)	-40%	40%
Wetlands Converted to Forest Land	**(3.2)**	**(3.4)**	**(3.1)**	**-5%**	**5%**
Aboveground Biomass	(1.4)	(1.5)	(1.2)	-10%	10%
Belowground Biomass	(0.3)	(0.3)	(0.2)	-12%	12%
Dead Wood	(0.4)	(0.4)	(0.3)	-11%	11%
Litter	(1.2)	(1.3)	(1.2)	-5%	5%
Mineral Soils	+	+	+	NA	NA
Total: Aboveground Biomass	**(55.1)**	**(66.0)**	**(44.2)**	**-20%**	**20%**
Total: Belowground Biomass	**(10.7)**	**(12.5)**	**(8.9)**	**-17%**	**17%**
Total: Dead Wood	**(11.8)**	**(13.6)**	**(10.0)**	**-15%**	**15%**
Total: Litter	**(20.4)**	**(22.0)**	**(18.8)**	**-8%**	**8%**
Total: Mineral Soils	**(1.1)**	**(1.7)**	**(0.6)**	**-49%**	**49%**
Total: Lands Converted to Forest Lands	**(99.1)**	**(110.4)**	**(87.8)**	**-11%**	**11%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

\+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

See QA/QC and Verification sections under *Forest Land Remaining Forest Land* and for mineral soil estimates *Cropland Remaining Cropland.*

Recalculations Discussion

The approach for estimating carbon stock changes in *Land Converted to Forest Land* is consistent with the methods used for *Forest Land Remaining Forest Land* and is described in Annex 3.13. The *Land Converted to Forest Land* estimates in this Inventory are based on the land use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass C stocks removed from Croplands and Grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil C stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots available through August 2020 were used in this Inventory. This is the second year that remeasurement data from the annual NFI were available throughout the CONUS (with the exception of Wyoming and western Oklahoma) to estimate land use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of C stocks and stock changes for *Forest Land Remaining Forest Land* and the *Land Converted to Forest Land* categories. Estimates in the previous Inventory were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this Inventory resulted in changes in the *Land Converted to Forest Land* categories. Overall, the *Land Converted to Forest Land* C stock changes decreased by 10 percent in 2018 between the previous Inventory and the current Inventory (Table 6-27). This decrease is directly attributed to the incorporation of annual NFI data into the compilation system. In the previous Inventory, *Grasslands Converted to Forest* Land represented the largest transfer and uptake of C across the land use conversion categories. In this Inventory, *Cropland Converted to Forest Land* represented the largest transfer and uptake of C across the land use change categories followed by *Settlements Converted to Forest Land* (Table 6-27).

Table 6-27: Recalculations of the Net C Flux from Forest C Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2018 Estimate, Previous Inventory	2018 Estimate, Current Inventory	2019 Estimate, Current Inventory
Cropland Converted to Forest Land	**(12.6)**	**(10.9)**	**(10.9)**
Aboveground Biomass	(7.2)	(6.3)	(6.3)
Belowground Biomass	(1.4)	(1.2)	(1.2)
Dead Wood	(1.6)	(1.4)	(1.4)
Litter	(2.3)	(1.9)	(1.9)
Mineral soil	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(2.6)**	**(2.9)**	**(2.9)**
Aboveground Biomass	(1.2)	(1.3)	(1.3)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.2)	(0.3)	(0.3)
Litter	(1.0)	(1.1)	(1.1)
Mineral soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(4.1)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.7)	(1.3)	(1.3)
Belowground Biomass	(0.3)	(0.2)	(0.2)
Dead Wood	(0.5)	(0.4)	(0.4)
Litter	(1.1)	(0.7)	(0.7)
Mineral soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(10.6)**	**(9.4)**	**(9.4)**
Aboveground Biomass	(6.4)	(5.7)	(5.7)
Belowground Biomass	(1.2)	(1.1)	(1.1)
Dead Wood	(1.2)	(1.1)	(1.1)
Litter	(1.7)	(1.5)	(1.5)
Mineral soil	+	+	+
Wetlands Converted to Forest Land	**(0.2)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.1)	(0.4)	(0.4)
Belowground Biomass	(0.0)	(0.1)	(0.1)
Dead Wood	(0.0)	(0.1)	(0.1)
Litter	(0.1)	(0.3)	(0.3)
Mineral soil	+	+	+

Total Aboveground Biomass Flux	(16.6)	(15.0)	(15.0)
Total Belowground Biomass Flux	(3.2)	(2.9)	(2.9)
Total Dead Wood Flux	(3.7)	(3.2)	(3.2)
Total Litter Flux	(6.3)	(5.6)	(5.6)
Total SOC (mineral) Flux	(0.3)	(0.3)	(0.3)
Total Flux	(30.2)	(27.0)	(27.0)

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake.

+ Absolute value does not exceed 0.05 MMT C.

Planned Improvements

There are many improvements necessary to improve the estimation of carbons stock changes associated with land use conversion to forest land over the entire time series. First, soil C has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. 2017) while other land-use categories (e.g., Grasslands and Croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all mineral soil estimates in the *Land Converted to Forest Land* category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil C to depths of 20, 30, and 100 cm in the Forest Land category using in situ measurements from the Forest Inventory and Analysis program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land use conversion categories and Domke et al. (2017) will be used in the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* categories to ensure consistent reporting across all forest land. Third, due to the 5 to 10-year remeasurement periods within the FIA program and limited land use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRF Category 4B1)

Carbon (C) in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, C storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, C is found in organic and inorganic forms of C, but soil organic C is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic C to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated

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[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the Inventory.

sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net C stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland Remaining Cropland includes all cropland in an Inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2018a) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

Cropland in Alaska is not included in the Inventory, but is a relatively small amount of U.S. cropland area (approximately 28,700 hectares). Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). This leads to a small discrepancy between the managed area in *Cropland Remaining Cropland* (see Table 6-31 in Planned Improvements for more details on the land area discrepancies) and the cropland area included in the Inventory analysis. Improvements are underway to include croplands in Alaska as part of future C inventories.

Land-use and land management of mineral soils are the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-28 and Table 6-29). In 2019, mineral soils are estimated to sequester 47.4 MMT CO_2 Eq. from the atmosphere (12.9 MMT C). This rate of C storage in mineral soils represents about a 18 percent decrease in the rate since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 32.9 MMT CO_2 Eq. (9.0 MMT C) in 2019, which is a 6 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 14.5 MMT CO_2 Eq. (4.0 MMT C) in 2019.

Table 6-28: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO₂ Eq.)

Soil Type	1990		2005		2015	2016	2017	2018	2019
Mineral Soils	(58.2)		(62.4)		(44.9)	(54.3)	(55.1)	(49.4)	(47.4)
Organic Soils	35.0		33.4		32.1	31.6	32.8	32.8	32.9
Total Net Flux	**(23.2)**		**(29.0)**		**(12.8)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**

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[39] N₂O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the Inventory.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Table 6-29: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	1990		2005		2015	2016	2017	2018	2019
Mineral Soils	(15.9)		(17.0)		(12.3)	(14.8)	(15.0)	(13.5)	(12.9)
Organic Soils	9.5		9.1		8.8	8.6	8.9	8.9	9.0
Total Net Flux	**(6.3)**		**(7.9)**		**(3.5)**	**(6.2)**	**(6.1)**	**(4.5)**	**(4.0)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic C stocks increase in *Cropland Remaining Cropland* largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments. However, there is a decline in the net amount of C sequestration (i.e., 2019 is 18 percent less than 1990), and this decline is due to lower sequestration rates in set-aside lands, less impact of manure amendments and annual crop production with hay and pasture in rotation. Soil organic C losses from drainage of organic soils are relatively stable across the time series with a small decline associated with the land base declining for *Cropland Remaining Cropland* on organic soils since 1990.

The spatial variability in the 2015 annual soil organic C stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of C accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas. In particular, higher rates of net C accumulation in mineral soils occur in the Corn Belt region, which is the region with the largest amounts of conservation tillage, along with moderate rates of CRP enrollment. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

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[41] Only national-scale emissions are estimated for 2016 to 2019 in this Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-6: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*
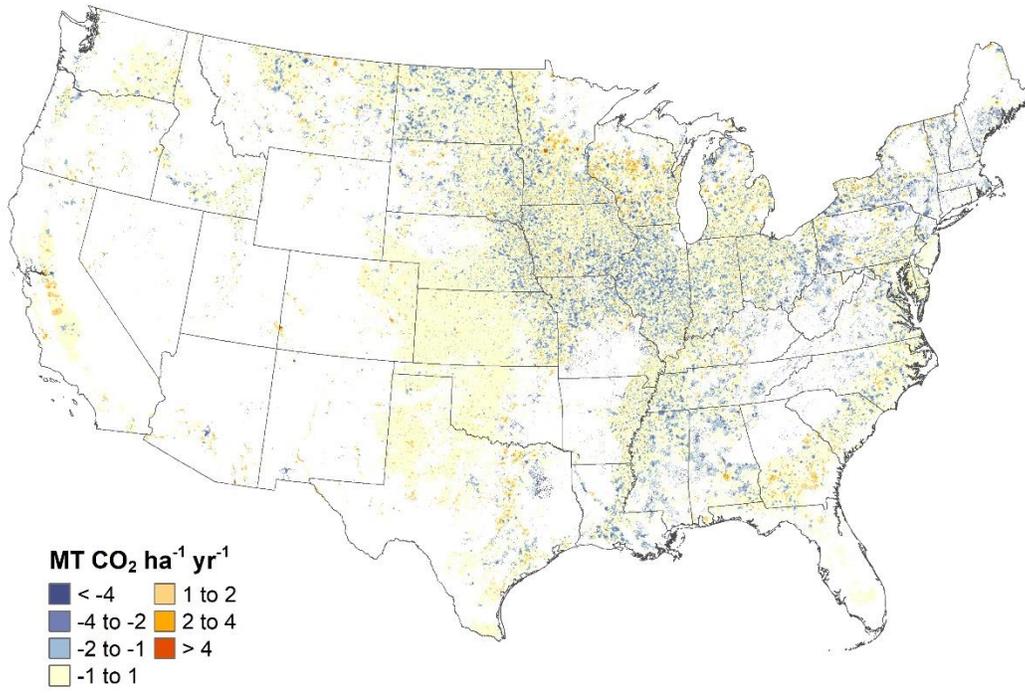
Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

Figure 6-7: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*

Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology
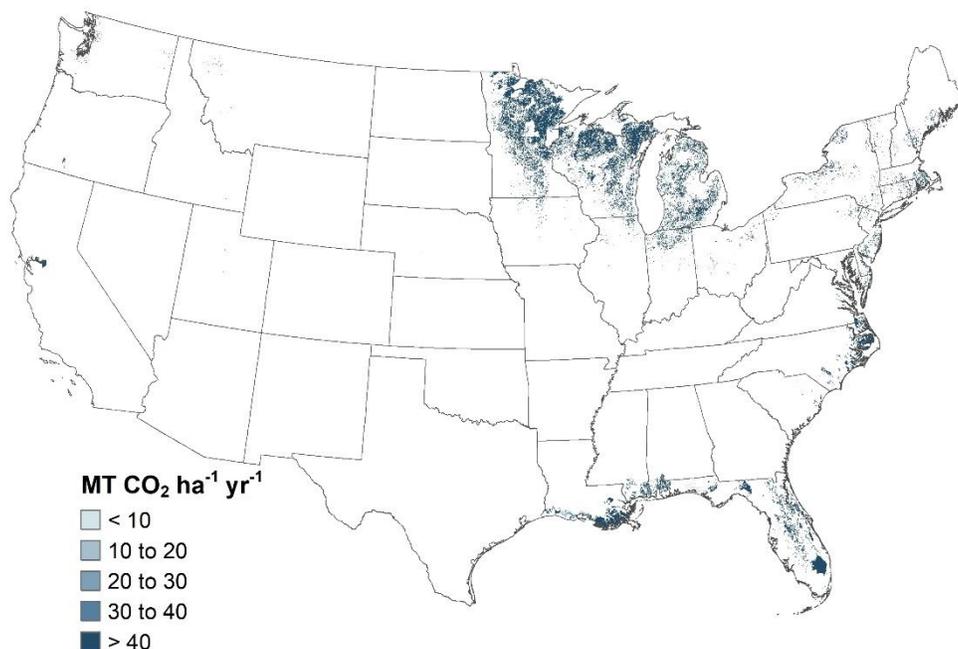
The following section includes a description of the methodology used to estimate changes in soil organic C stocks for *Cropland Remaining Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic C stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate C stock changes across most of the time series, a surrogate data method has been applied to estimate stock changes in the last few years of the Inventory. Stock change estimates based on surrogate data will be recalculated in a future Inventory report using the Tier 2 and 3 methods when data become available.

Soil organic C stock changes on non-federal lands are estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2018a). The NRI is a statistically-based sample of all non-federal land, and includes approximately 489,178 survey locations in agricultural land for the conterminous United States and Hawaii. Each survey location is associated with an "expansion factor" that allows scaling of C stock changes from NRI survey locations to the entire country

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[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

(i.e., each expansion factor represents the amount of area that is expected to have the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018a). NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2015 if the land use has been cropland for a continuous time period of at least 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Cropland Remaining Cropland* in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic C stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, but is not applied to estimate organic C stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic C stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and N dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic C stock changes on federal croplands. Mineral soil organic C stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2019 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2018). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2016 to 2019 will be recalculated in future inventories when new NRI data are available.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic C stock changes in *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. A linear regression model with autoregressive moving-average

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[43] See <https://quickstats.nass.usda.gov/>.

(ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2015 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), $X\beta$ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2015 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2016 to 2019.

A critical issue with application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2015), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95% confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic C stocks and stock changes are estimated to a 30 cm depth using the DayCent biogeochemical[44] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of C, N, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[45] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2018), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

Box 6-5: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic C stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic C stock

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[44] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

[45] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2015. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic C stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.

2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at about 350,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in C stocks that assumes a step-change from one equilibrium level of the C stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of C stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil organic C stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018a). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. These data are combined with other datasets in an imputation analysis that extend the time series from 1990 to 2015. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information across several datasets (discussed below), b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994), and c) assign management practices from the CEAP survey to the specific NRI locations using predictive mean matching methods that is adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a very large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. Predictive mean matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments from 1979 to 2015, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of a data collection program known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2018). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both rates. This approach captures the relationship between mineral fertilization and manure amendment practices for U.S. croplands based directly on the observed patterns in the CEAP survey data.

To determine the trends in tillage management from 1979 to 2015, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and USDA-ERS Agriculture Resource Management Surveys (ARMS) data from 2002 to 2015 (Claasen et al. 2018). CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). It is assumed that the majority of agricultural lands are managed with full tillage prior to 1985. For cover crops, CEAP data are combined with information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover cropping was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management derived from the CEAP survey.

Uncertainty in the C stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of C and N dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. To assess input uncertainty, The C and N dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator as described in Ogle et al. (2007, 2010). Sampling uncertainty is assessed using the NRI replicate sampling weights.

Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015 using the DayCent model. However, note that the areas have been modified in the original NRI survey through the process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015) are harmonized with the NRI data. This process ensures that the areas of *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* are consistent with other land use categories while maintaining a consistent time series for the total land area of the United States. For example, if the FIA estimate less *Cropland Converted to Forest Land* than the NRI, then the amount of area for this land use conversion is reduced in the NRI dataset and re-classified as *Cropland Remaining Cropland* (See Section 6, Representation of the U.S. Land Base for more information). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

Soil organic C stock changes from 2016 to 2019 are estimated using a surrogate data method that is described in Box 6-4. Future Inventories will be updated with new NRI activity data when the data are made available, and the time series from 2016 to 2019 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic C stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2015 NRI survey (USDA-NRCS 2018a). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. The one exception are activity data on wetland restoration of Conservation Reserve Program land that are obtained from Euliss and Gleason (2002). Climate zones in the United States are classified using mean precipitation and temperature (1950 to 2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008, 2007) (Figure A-9). IPCC climate zones are then assigned to NRI survey locations.

Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific C stock change

factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Changes in soil organic C stocks for mineral soils are estimated 1,000 times for 1990 through 2015, using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2003; Ogle et al. 2006). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

Soil organic C stock changes from 2016 to 2019 are estimated using a surrogate data method that is described in Box 6-4. As with the Tier 3 method, future Inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated (see Planned Improvements section).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates include a measure of uncertainty as determined from a Monte Carlo Simulation with 1,000 iterations. Emissions are based on the land area data for drained organic soils from 1990 to 2015 for *Cropland Remaining Cropland* in the 2015 NRI (USDA-NRCS 2018a). Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

A surrogate data method was used to estimate annual C emissions from organic soils from 2016 to 2019 as described in Box 6-4 of this section. Estimates for 2016 to 2019 will be recalculated in future Inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

Uncertainty is quantified for changes in soil organic C stocks associated with *Cropland Remaining Cropland* (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-30 for each subsource (mineral and organic soil C stocks) and the methods that are used in the Inventory analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived using a Monte Carlo approach (see Annex 3.12 for further discussion). For 2016 to 2019, additional uncertainty is propagated through the Monte Carlo Analysis that is associated with the surrogate data method. Soil organic C stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Cropland Remaining Cropland* ranges from 601 percent below to 601 percent above the 2019 stock change estimate of -14.5 MMT CO_2 Eq. The large relative uncertainty around the 2019 stock change estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-30: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO₂ Eq. and Percent)

Source	2019 Flux Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO₂ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(41.5)	(126.6)	43.5	-205%	205%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(5.9)	(12.5)	0.8	-114%	114%

Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	32.9	13.8	51.9	-58%	58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(14.5)**	**(102.0)**	**72.9**	**-601%**	**601%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter C stock changes. However, woody biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass C stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the Inventory time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 72 long-term experiment sites and 142 NRI soil monitoring network sites, with 948 observations across all of the sites (see Annex 3.12 for more information).

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A key improvement for a future Inventory will be to incorporate additional management activity data from the USDA-NRCS Conservation Effects Assessment Project survey. This survey has compiled new data in recent years that will be available for the Inventory analysis by next year. The latest land use data will also be incorporated from the USDA National Resources Inventory and related management data from USDA-ERS ARMS surveys.

There are several other planned improvements underway related to the plant production module. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce the bias in model predictions for grasslands, which was discovered through model evaluation by comparing output to measurement data from 72 experimental sites and 142 NRI soil monitoring network sites (See QA/QC and Verification section).

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the Field Burning of Agricultural Residues source category (see Section 5.7). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning.

A review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

In the future, the Inventory will include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data. See Table 6-31 for the amount of managed area in *Cropland Remaining Cropland* that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and also other miscellaneous cropland areas, such as aquaculture.

Many of these improvements are expected to be completed for the 1990 through 2020 Inventory (i.e., 2021 submission to the UNFCCC). However, the timeline may be extended if there are insufficient resources to fund all or part of these planned improvements.

Table 6-31: Area of Managed Land in *Cropland Remaining Cropland* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	162,163	162,134	29
1991	161,721	161,692	29
1992	161,252	161,223	29
1993	159,449	159,420	29
1994	157,732	157,703	29
1995	157,054	157,025	29
1996	156,409	156,380	29
1997	155,767	155,738	29
1998	152,016	151,987	29
1999	151,135	151,105	29
2000	150,981	150,952	29
2001	150,471	150,442	29
2002	150,175	150,146	29
2003	150,843	150,814	29
2004	150,645	150,616	29
2005	150,304	150,275	29
2006	149,791	149,762	29
2007	150,032	150,003	29
2008	149,723	149,694	29
2009	149,743	149,714	29
2010	149,343	149,314	29
2011	148,844	148,815	29
2012	148,524	148,495	29
2013	149,018	148,989	29
2014	149,492	149,463	29
2015	148,880	148,851	29
2016	ND	ND	ND
2017	ND	ND	ND

| 2018 | ND | ND | ND |
| 2019 | ND | ND | ND |

Note: NRI data are not available after 2015, and so these years are designated as ND (No data).

6.5 Land Converted to Cropland (CRF Category 4B2)

Land Converted to Cropland includes all cropland in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all croplands in the conterminous United States and Hawaii, but does not include a minor amount of *Land Converted to Cropland* in Alaska. Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas dynamics in management systems (e.g., aquaculture). Consequently, there is a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 6 Representation of the U.S. Land Base) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and miscellaneous croplands in future C inventories (see Table 6-35 in the Planned Improvements section for more details on the land area discrepancies).

Land-use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use change. All soil organic C stock changes are estimated and reported for *Land Converted to Cropland*, but reporting of C stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to *Forest Land Converted to Cropland.*[46]

Forest Land Converted to Cropland is the largest source of emissions from 1990 to 2019, accounting for approximately 87 percent of the average total loss of C among all of the land use conversions in *Land Converted to Cropland*. The pattern is due to the large losses of biomass and dead organic matter C for *Forest Land Converted to Cropland*. The next largest source of emissions is *Grassland Converted to Cropland* accounting for approximately 17 percent of the total emissions (Table 6-32 and Table 6-33).

The net change in total C stocks for 2019 led to CO_2 emissions to the atmosphere of 54.2 MMT CO_2 Eq. (14.8 MMT C), including 28.3 MMT CO_2 Eq. (7.7 MMT C) from aboveground biomass C losses, 5.6 MMT CO_2 Eq. (1.5 MMT C) from belowground biomass C losses, 5.5 MMT CO_2 Eq. (1.5 MMT C) from dead wood C losses, 8.1 MMT CO_2 Eq. (2.2 MMT C) from litter C losses, 3.0 MMT CO_2 Eq. (0.8 MMT C) from mineral soils and 3.7 MMT CO_2 Eq. (1.0 MMT C) from drainage and cultivation of organic soils. Emissions in 2019 are 5 percent higher than emissions in the initial reporting year, i.e., 1990.

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[46] Changes in biomass C stocks are not currently reported land use conversions to cropland except for forest land converted to cropland, but this is a planned improvement for a future inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions to cropland, except forest land.

Table 6-32: Net CO₂ Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Land Converted to Cropland* **by Land Use Change Category (MMT CO₂ Eq.)**

	1990	2005	2015	2016	2017	2018	2019
Grassland Converted to Cropland	**6.9**	**7.5**	**10.2**	**8.5**	**8.7**	**8.5**	**8.4**
Mineral Soils	4.1	4.0	6.9	5.2	5.4	5.1	5.1
Organic Soils	2.7	3.5	3.3	3.3	3.3	3.3	3.3
Forest Land Converted to Cropland	**46.3**	**46.8**	**47.5**	**47.6**	**47.6**	**47.6**	**47.6**
Aboveground Live Biomass	27.3	27.7	28.2	28.3	28.3	28.3	28.3
Belowground Live Biomass	5.4	5.5	5.6	5.6	5.6	5.6	5.6
Dead Wood	5.4	5.5	5.5	5.5	5.5	5.5	5.5
Litter	7.7	7.9	8.1	8.1	8.1	8.1	8.1
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Other Lands Converted to Cropland	**(2.2)**	**(2.9)**	**(2.0)**	**(2.1)**	**(2.2)**	**(2.2)**	**(2.3)**
Mineral Soils	(2.3)	(2.9)	(2.0)	(2.1)	(2.2)	(2.2)	(2.3)
Organic Soils	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland	**0.8**	**0.9**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**
Mineral Soils	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Organic Soils	0.6	0.6	0.3	0.3	0.3	0.4	0.4
Aboveground Live Biomass	**27.3**	**27.7**	**28.2**	**28.3**	**28.3**	**28.3**	**28.3**
Belowground Live Biomass	**5.4**	**5.5**	**5.6**	**5.6**	**5.6**	**5.6**	**5.6**
Dead Wood	**5.4**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Litter	**7.7**	**7.9**	**8.1**	**8.1**	**8.1**	**8.1**	**8.1**
Total Mineral Soil Flux	**2.3**	**1.3**	**5.0**	**3.3**	**3.4**	**3.1**	**3.0**
Total Organic Soil Flux	**3.7**	**4.3**	**3.7**	**3.7**	**3.7**	**3.7**	**3.7**
Total Net Flux	**51.8**	**52.2**	**56.1**	**54.4**	**54.6**	**54.3**	**54.2**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO₂ Eq.

Table 6-33: Net CO₂ Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Land Converted to Cropland* **(MMT C)**

	1990	2005	2015	2016	2017	2018	2019
Grassland Converted to Cropland	**1.9**	**2.0**	**2.8**	**2.3**	**2.4**	**2.3**	**2.3**
Mineral Soils	1.1	1.1	1.9	1.4	1.5	1.4	1.4
Organic Soils	0.7	1.0	0.9	0.9	0.9	0.9	0.9
Forest Land Converted to Cropland	**12.6**	**12.8**	**13.0**	**13.0**	**13.0**	**13.0**	**13.0**
Aboveground Live Biomass	7.4	7.6	7.7	7.7	7.7	7.7	7.7
Belowground Live Biomass	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Dead Wood	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Litter	2.1	2.2	2.2	2.2	2.2	2.2	2.2
Mineral Soils	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Organic Soils	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other Lands Converted to Cropland	**(0.6)**	**(0.8)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**
Mineral Soils	(0.6)	(0.8)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Organic Soils	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**	**(0.0)**
Mineral Soils	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Organic Soils	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wetlands Converted to Cropland	**0.2**	**0.3**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Mineral Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**7.4**	**7.6**	**7.7**	**7.7**	**7.7**	**7.7**	**7.7**
Belowground Live Biomass	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

Dead Wood	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Litter	2.1	2.2	2.2	2.2	2.2	2.2	2.2
Total Mineral Soil Flux	0.6	0.4	1.4	0.9	0.9	0.8	0.8
Total Organic Soil Flux	1.0	1.2	1.0	1.0	1.0	1.0	1.0
Total Net Flux	14.1	14.2	15.3	14.8	14.9	14.8	14.8

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT C.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Cropland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic C stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for *Forest Land Converted to Cropland.* Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020). However, there are no country-specific data for cropland biomass, so default biomass values (IPCC 2006) were used to estimate the carbon stocks for the new cropland (litter and dead wood carbon stocks were assumed to be zero since no reference C density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for *Land Converted to Cropland* according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as *Land Converted to Cropland* in a given year between 1990 and 2015 if the land use is cropland but had been another use during the previous 20 years. NRI survey

locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of *Land Converted to Cropland* in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat. Soil organic C stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2016 to 2019, a surrogate data method is used to estimate soil organic C stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2015). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2019 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. For the Tier 3 method, mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

Soil organic C stock changes from 2016 to 2019 were estimated using the surrogate data method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see the Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Cropland Remaining Cropland*. This includes application of the surrogate data method that is described in Box 6-4of the Methodology section in *Cropland Remaining Cropland*. As with the Tier 3 method, future inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland*

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[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[48] See <https://quickstats.nass.usda.gov/>.

Remaining Cropland section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

The Inventory analysis includes application of the surrogate data method that is described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Cropland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in *Cropland Remaining Cropland* (Also see Annex 3.12 for further discussion). The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2019, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-34 for each subsource (i.e., biomass C stocks, dead wood C stocks, litter C stocks, soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total C stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Cropland* ranged from 102 percent below to 103 percent above the 2019 stock change estimate of 54.2 MMT CO_2 Eq. The large relative uncertainty in the 2019 estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-34: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Cropland* (MMT CO_2 Eq. and Percent)

Source	2018 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**8.4**	**(31.1)**	**48.0**	**-468%**	**468%**
Mineral Soil C Stocks: Tier 3	0.8	(38.5)	40.2	-4767%	4767%
Mineral Soil C Stocks: Tier 2	4.3	1.3	7.3	-70%	70%
Organic Soil C Stocks: Tier 2	3.3	0.8	5.8	-75%	75%
Forest Land Converted to Cropland	**47.6**	**8.8**	**87.2**	**-81%**	**83%**
Aboveground Live Biomass	28.3	(7.7)	64.7	-127%	129%
Belowground Live Biomass	5.6	(1.5)	12.8	-127%	129%
Dead Wood	5.5	(1.6)	13.3	-129%	141%
Litter	8.1	(2.3)	19.4	-129%	140%
Mineral Soil C Stocks: Tier 2	0.1	+	0.3	-136%	136%
Organic Soil C Stocks: Tier 2	+	(0.1)	0.1	-1350%	1350%
Other Lands Converted to Cropland	**(2.3)**	**(3.7)**	**(0.9)**	**-61%**	**61%**
Mineral Soil C Stocks: Tier 2	(2.3)	(3.7)	(0.9)	-61%	61%
Organic Soil C Stocks: Tier 2	+	+	+	+	+
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	**+**	**-111%**	**111%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	+	-86%	86%
Organic Soil C Stocks: Tier 2	+	+	0.1	-84%	84%

Wetlands Converted to Croplands	**0.6**	**+**	**1.2**	**-96%**	**96%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.5	-105%	105%
Organic Soil C Stocks: Tier 2	0.4	(0.2)	0.9	-141%	141%
Total: Land Converted to Cropland	**54.2**	**(1.2)**	**110.2**	**-102%**	**103%**
Aboveground Live Biomass	**28.3**	**(7.7)**	**64.7**	**-127%**	**129%**
Belowground Live Biomass	**5.6**	**(1.5)**	**12.8**	**-127%**	**129%**
Dead Wood	**5.5**	**(1.6)**	**13.3**	**-129%**	**141%**
Litter	**8.1**	**(2.3)**	**19.4**	**-129%**	**140%**
Mineral Soil C Stocks: Tier 3	**0.8**	**(38.5)**	**40.2**	**-4767%**	**4767%**
Mineral Soil C Stocks: Tier 2	**2.2**	**(1.1)**	**5.5**	**-151%**	**151%**
Organic Soil C Stocks: Tier 2	**3.7**	**1.2**	**6.3**	**-68%**	**68%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass C stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter C stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future Inventory.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* for information on QA/QC steps.

Recalculations Discussion

Differences in biomass, dead wood and litter C stock changes in *Forest Land Converted to Cropland* can be attributed to incorporation of the latest FIA data for 1990 to 2019. As a result of these new data, *Land Converted to Cropland* has a marginally smaller reported loss of C compared to the previous Inventory, estimated at an average of 1.7 MMT CO_2 Eq. over the time series. This represents a 3 percent decline in losses of C for *Land Converted to Cropland* compared to the previous Inventory.

Planned Improvements

Planned improvements are underway to include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data that drive C stock changes on long-term cropland. See Table 6-35 for the amount of managed area in *Land Converted to Cropland* that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and other miscellaneous cropland areas, such as aquaculture. Additional planned improvements are discussed in the Planned Improvements section of *Cropland Remaining Cropland*.

Table 6-35: Area of Managed Land in *Land Converted to Cropland* that is not included in the current Inventory (Thousand Hectares)

Year	Area (Thousand Hectares)		
	Managed Land	Inventory	Not Included in Inventory
1990	12,308	12,308	<1
1991	12,654	12,654	<1
1992	12,943	12,943	<1
1993	14,218	14,218	<1
1994	15,400	15,400	<1
1995	15,581	15,581	<1
1996	15,888	15,888	<1
1997	16,073	16,073	<1
1998	17,440	17,440	<1
1999	17,819	17,819	<1
2000	17,693	17,693	<1
2001	17,600	17,600	<1
2002	17,487	17,487	<1
2003	16,257	16,257	<1
2004	15,317	15,317	<1
2005	15,424	15,424	<1
2006	15,410	15,410	<1
2007	14,923	14,923	<1
2008	14,399	14,399	<1
2009	13,814	13,814	<1
2010	13,905	13,905	<1
2011	14,186	14,186	<1
2012	14,429	14,429	<1
2013	13,752	13,752	<1
2014	13,050	13,050	<1
2015	13,049	13,049	<1
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND

Note: NRI data are not available after 2015 so these years are designated as ND (No data).

6.6 Grassland Remaining Grassland (CRF Category 4C1)

Carbon (C) in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of C in grasslands, and have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use and management. C stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands), and may be extended to include agroforestry management associated with grasslands in the future. For soil

organic C, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[49]

Grassland Remaining Grassland includes all grassland in an Inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (See Land Representation section for more information about the criteria for forest land). The current Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include approximately 50 million hectares of *Grassland Remaining Grassland* in Alaska. This leads to a discrepancy with the total amount of managed area in *Grassland Remaining Grassland* (see Table 6-39 in Planned Improvements for more details on the land area discrepancies) and the grassland area included in the Inventory analysis.

In *Grassland Remaining Grassland*, there has been considerable variation in C stocks between 1990 and 2019. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total C stocks for 2019 led to net CO_2 emissions to the atmosphere of 14.5 MMT CO_2 Eq. (4.0 MMT C), including 1.3 MMT CO_2 Eq. (0.4 MMT C) from net losses of aboveground biomass C, 0.1 MMT CO_2 Eq. (<0.05 MMT C) from net losses in belowground biomass C, 2.3 MMT CO_2 Eq. (0.6 MMT C) from net losses in dead wood C, 0.2 MMT CO_2 Eq. (<0.05 MMT C) from net gains in litter C, 5.5 MMT CO_2 Eq. (1.5 MMT C) from net losses in mineral soil organic C, and 5.4 MMT CO_2 Eq. (1.5 MMT C) from losses of C due to drainage and cultivation of organic soils (Table 6-36 and Table 6-37). Losses of carbon are 74 percent higher in 2019 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2019, with an average annual change of 8.7 MMT CO_2 Eq. (2.4 MMT C).

Table 6-36: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Grassland Remaining Grassland* (MMT CO_2 Eq.)

Soil Type	1990	2005	2015	2016	2017	2018	2019
Aboveground Live Biomass	1.4	1.4	1.4	1.4	1.4	1.3	1.3
Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	2.8	2.7	2.4	2.4	2.4	2.4	2.3
Litter	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Mineral Soils	(2.2)	0.8	4.0	0.7	2.2	2.7	5.5
Organic Soils	6.3	5.2	5.4	5.4	5.4	5.4	5.4
Total Net Flux	**8.3**	**10.0**	**13.1**	**9.8**	**11.3**	**11.7**	**14.5**

Table 6-37: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in *Grassland Remaining Grassland* (MMT C)

Soil Type	1990	2005	2015	2016	2017	2018	2019
Aboveground Live Biomass	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	0.8	0.7	0.7	0.7	0.7	0.6	0.6
Litter	+	+	+	+	+	+	+
Mineral Soils	(0.6)	0.2	1.1	0.2	0.6	0.7	1.5
Organic Soils	1.7	1.4	1.5	1.5	1.5	1.5	1.5
Total Net Flux	**2.3**	**2.7**	**3.6**	**2.7**	**3.1**	**3.2**	**4.0**

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[49] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

The spatial variability in soil organic C stock changes for 2015[50] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained C in isolated areas that mostly occurred in pastures of the eastern United States. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

Figure 6-8: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*
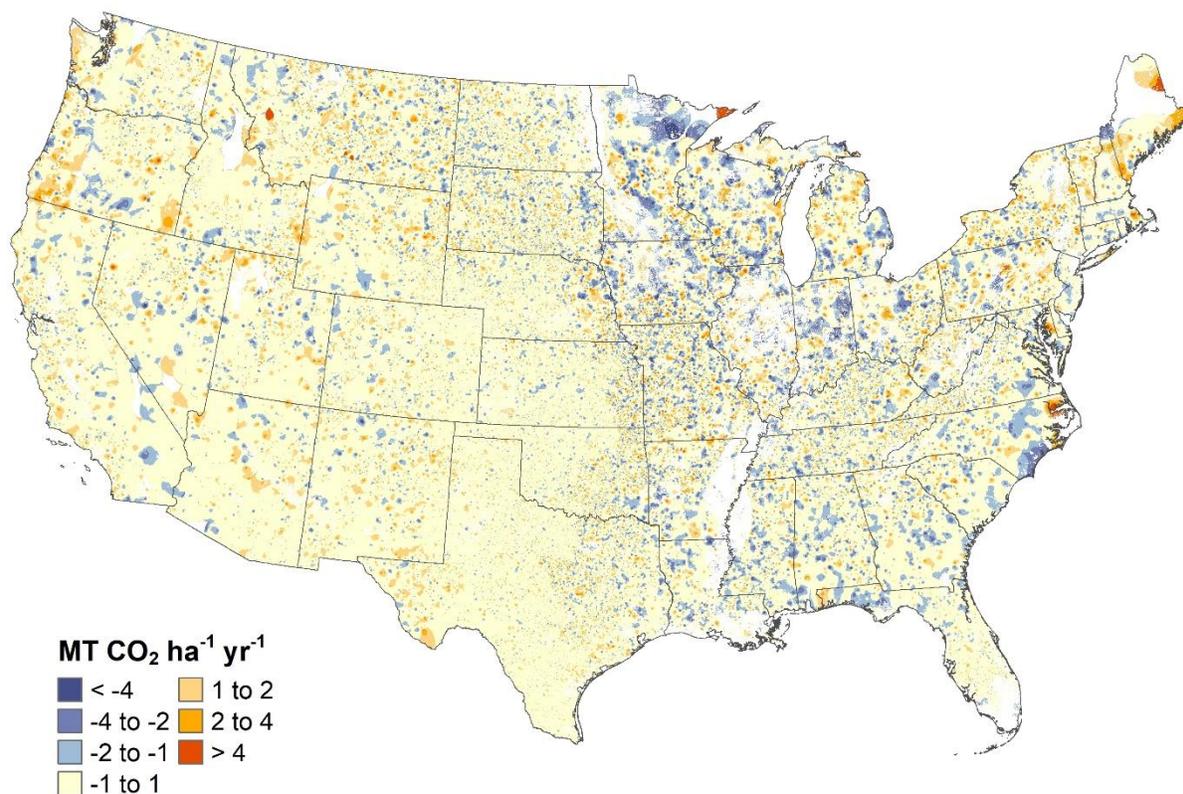
Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

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[50] Only national-scale emissions are estimated for 2016 to 2019 in the current Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-9: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*

MT CO_2 ha^{-1} yr^{-1}
- ☐ < 10
- ☐ 10 to 20
- ☐ 20 to 30
- ☐ 30 to 40
- ■ > 40
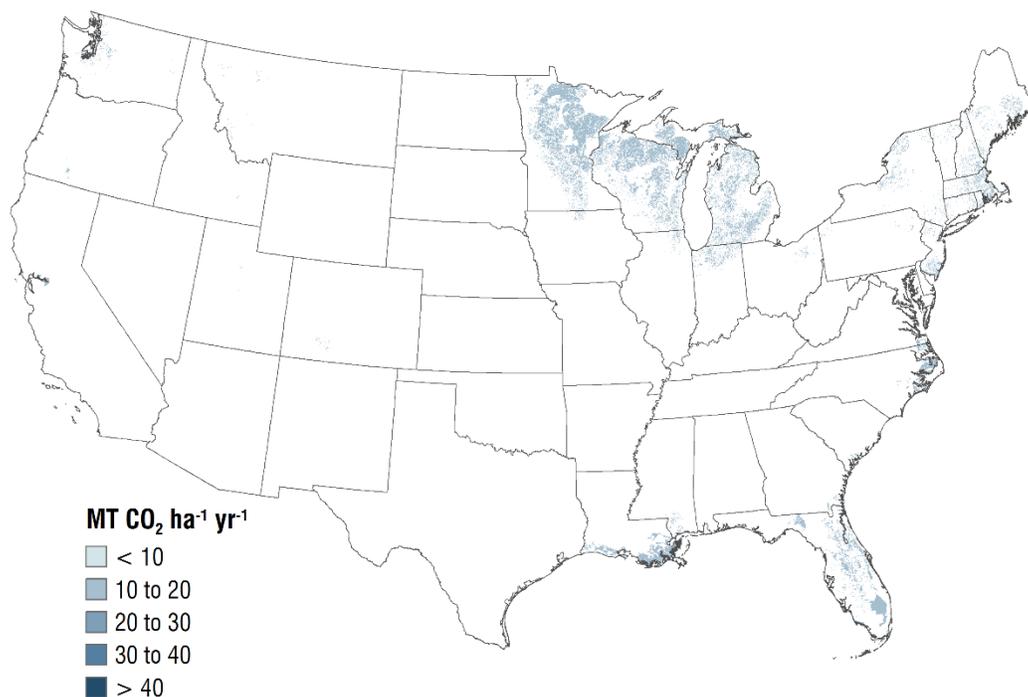
Note: Only national-scale soil organic carbon stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Grassland Remaining Grassland*, including (1) aboveground and belowground biomass, dead wood and litter C for woodlands, as well as (2) soil organic C stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

The methodology is consistent with IPCC (2006). Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6 Representation of the U.S. Land Base), but include woody vegetation with C storage in aboveground and belowground biomass, dead wood and litter C (IPCC 2006) as described in the *Forest Land Remaining Forest Land* section. Carbon stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in *Grassland Land Remaining Grassland* are consistent with those in the *Forest Land Remaining Forest Land* section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2020) were used in the current Inventory. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland.

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic C stocks for *Grassland Remaining Grassland*, including: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil organic C stock changes are estimated for *Grassland Remaining Grassland* on non-federal lands according to land use histories recorded in the 2015 USDA NRI survey (USDA-NRCS 2018). Land-use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2015). NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2015 if the land use had been grassland for 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Grassland Remaining Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), the additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments, and federal land.[51]

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2019 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2019 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. Mineral soil organic C stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DayCent biogeochemical[52] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018).

The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 Manure Management and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) is an input to the DayCent model to estimate the influence of PRP manure on C stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence

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[51] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[52] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

intervals are estimated for each year between 1990 and 2015 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

Soil organic C stock changes from 2016 to 2019 were estimated using a surrogate data method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Future Inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see the Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils, with the exception of the manure N deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the Inventory for federal grasslands. First, the PRP N manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2018) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic C stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

The time series of stock changes for non-federal and federal lands has been extended from 2016 to 2019 using a surrogate data method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*.

Additional Mineral C Stock Change Calculations

A Tier 2 method is used to adjust annual C stock change estimates for mineral soils between 1990 and 2019 to account for additional C stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids N applied to agricultural land are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in *Grassland Remaining Grassland*. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic C storage rate is estimated at 0.38 metric tons C per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the *Cropland Remaining Cropland* section for organic soils and Annex 3.12.

A surrogate data method was used to estimate annual C emissions from organic soils from 2016 to 2019 as described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Estimates for 2016 to 2019 will be updated in future Inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Cropland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Grassland Remaining Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2019, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-38 for each subsource (i.e., soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Grassland Remaining Grassland* ranges from more than 1,066 percent below and above the 2019 stock change estimate of 14.5 MMT CO_2 Eq. The large relative uncertainty is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO₂ Eq. and Percent)

Source	2019 Flux Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO₂ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	1.3	0.9	1.7	-31%	31%
Belowground live biomass	0.1	0.1	0.1	16%	16%
Dead wood	2.3	1.8	2.8	-22%	22%
Litter	(0.2)	(0.3)	+	-105%	105%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	5.7	(148.9)	160.3	-2,712%	2,712%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	+	(0.9)	0.9	-5,287%	5,287%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(0.2)	(0.3)	(0.1)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.4	1.2	9.6	-77%	77%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**14.5**	**(140.2)**	**169.2**	**-1,066%**	**1,066%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

+ Does not exceed 0.05 MMT CO₂ Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. Changes in biomass and dead organic matter C stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are certainly significant changes at sub-annual time scales across seasons.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2018 on biomass, dead wood and litter C stocks in woodlands, and updated estimates for mineral soils from 2016 to 2018 using revised surrogate data. As a result of these new data, *Grassland Remaining Grassland* has a small loss of C compared to the previous Inventory, estimated at an average reduction in losses of 0.59 MMT CO_2 Eq. over the time series. This represents a 14 percent decrease in losses of C for *Grassland Remaining Grassland* compared to the previous Inventory.

Planned Improvements

Grasslands in Alaska are not currently included in the Inventory. This is a significant planned improvement and estimates are expected to be available in a future Inventory contingent on funding availability. Table 6-39 provides information on the amount of managed area in Alaska that is *Grassland Remaining Grassland*, which includes about 50 million hectares per year. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

Table 6-39: Area of Managed Land in *Grassland Remaining Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	327,446	277,406	50,040
1991	326,959	276,918	50,040
1992	326,462	276,422	50,040
1993	324,524	274,484	50,040
1994	322,853	272,813	50,040
1995	322,015	271,975	50,040
1996	321,164	271,123	50,040
1997	320,299	270,259	50,040
1998	318,214	268,174	50,040
1999	317,341	267,301	50,040
2000	316,242	266,202	50,040
2001	315,689	265,649	50,040
2002	315,232	265,192	50,040
2003	315,442	265,403	50,039
2004	315,459	265,421	50,038
2005	315,161	265,123	50,038
2006	314,841	264,804	50,037

2007	314,786	264,749	50,036
2008	314,915	264,878	50,037
2009	315,137	265,099	50,037
2010	314,976	264,942	50,035
2011	314,662	264,627	50,035
2012	314,466	264,413	50,053
2013	315,301	265,239	50,062
2014	316,242	266,180	50,062
2015	316,287	266,234	50,053
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Non-CO₂ Emissions from Grassland Fires (CRF Source Category 4C1)

Fires are common in grasslands, and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes, but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grassland of the United States (Including burning emissions in *Grassland Remaining Grassland* and *Land Converted to Grassland*) is a relatively small source of emissions, but it has increased by over 300 percent since 1990. In 2019, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2019 have averaged approximately 0.3 MMT CO_2 Eq. (12 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-40 and Table 6-41).

Table 6-40: CH₄ and N₂O Emissions from Biomass Burning in Grassland (MMT CO₂ Eq.)

	1990		2005		2015	2016	2017	2018	2019
CH_4	0.1		0.3		0.3	0.3	0.3	0.3	0.3
N_2O	0.1		0.3		0.3	0.3	0.3	0.3	0.3
Total Net Flux	**0.2**		**0.7**		**0.7**	**0.6**	**0.6**	**0.6**	**0.6**

Table 6-41: CH₄, N₂O, CO, and NOₓ Emissions from Biomass Burning in Grassland (kt)

	1990		2005		2015	2016	2017	2018	2019
CH_4	3		13		13	12	12	12	12
N_2O	+		1		1	1	1	1	1
CO	84		358		356	324	345	331	341
NO_x	5		22		21	20	21	20	20

+ Does not exceed 0.5 kt.

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[53] A planned improvement is underway to incorporate woodland tree biomass into the Inventory.

Methodology

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this Inventory, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2014 (IPCC 2006). A data splicing method is used to estimate the emissions in 2015 to 2019, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2015). NRI has survey locations across the entire United States, but does not classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6 Representation of the U.S. Land Base).

The area of biomass burning in grasslands (*Grassland Remaining Grassland* and *Land Converted to Grassland*) is determined using 30-m fire data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2014.[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within a 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-42).

Table 6-42: Thousands of Grassland Hectares Burned Annually

Year	Thousand Hectares
1990	317
2005	1,343
2014	1,659
2015	NE
2016	NE
2017	NE
2018	NE
2019	NE

Notes: Burned area was not estimated (NE) for 2015 to 2019 but will be updated in a future Inventory.

For 1990 to 2014, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this Inventory, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g CH_4 per kg dry matter), CO (65 g CH_4 per kg dry matter) and NO_x (3.9 g CH_4 per kg dry matter) (IPCC 2006). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[55]

A linear extrapolation of the trend in the time series is applied to estimate the emissions for 2015 to 2019 because new activity data have not been compiled for these years. Specifically, a linear regression model with

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[54] See <http://www.mtbs.gov>.

[55] See <http://www.nrel.colostate.edu/projects/ALUsoftware/>.

autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2014, and the trend is used to approximate the 2015 to 2019 emissions. The Tier 1 method described previously will be applied to recalculate the 2015 to 2019 emissions in a future Inventory.

Uncertainty and Time-Series Consistency

Emissions are estimated using a linear regression model with ARMA errors for 2015 to 2019. The linear regression ARMA model produced estimates of the upper and lower bounds of the emission estimate and the results are summarized in Table 6-43. Methane emissions from Biomass Burning in Grassland for 2018 are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 146 percent above the 2019 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq., or approximately 100 percent below and 146 percent above the 2019 emission estimate of 0.3 MMT CO_2 Eq.

Table 6-43: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.7	-100%	146%
Grassland Burning	N_2O	0.3	+	0.8	-100%	146%

+ Does not exceed 0.05 MMT CO_2 Eq.
[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grassland of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the Inventory. There is also uncertainty due to lack of reporting combustion of woody biomass, and this is another planned improvement.

There were no methodological recalculations in this Inventory, but data splicing methods to extend the time series for another year were applied in a manner to be consistent with the previous Inventory. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Quality control identified problems with input data for common reporting format tables in the spreadsheets, which have been corrected.

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A splicing data method is applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for the next Inventory will be to update the time series with new activity data from the Monitoring Trends in Burn Severity program and recalculate the emissions. Two other planned improvements have been identified for this source category, including a)

incorporation of country-specific grassland biomass factors, and b) extending the analysis to include Alaska. In the current Inventory, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Both improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRF Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018).[56] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include *Land Converted to Grassland* in Alaska. Consequently, there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Table 6-47 in Planned Improvements) and the grassland area included in the inventory analysis.

Land use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for *Land Converted to Grassland*, but there is limited reporting of other pools in this Inventory. Losses of aboveground and belowground biomass, dead wood and litter C from *Forest Land Converted to Grassland* are reported, but these C stock changes are not estimated for other land use conversions to grassland.[57]

The largest C losses with *Land Converted to Grassland* are associated with aboveground biomass, belowground biomass, and litter C losses from *Forest Land Converted to Grassland* (see Table 6-44 and Table 6-45). These three pools led to net emissions in 2019 of 8.6, 2.1, and 4.6 MMT CO_2 Eq. (2.4, 0.6, and 1.3 MMT C), respectively. Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil organic C stocks, estimated at 39.8 MMT CO_2 Eq. (10.9 MMT C) in 2019. The gains are primarily associated with conversion of Other Land, which have relatively low soil organic C stocks, to Grassland that tend to have conditions suitable for storing larger amounts of C in soils, and also due to conversion of Cropland to Grassland that leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the

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[56] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[57] Changes in biomass C stocks are not currently reported for other conversions to grassland (other than forest land), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

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atmosphere of 1.8 MMT CO_2 Eq. (0.5 MMT C). The total net C stock change in 2019 for *Land Converted to Grassland* is estimated as a gain of 23.2 MMT CO_2 Eq. (6.3 MMT C), which represents an increase in C stock changes of 271 percent compared to the initial reporting year of 1990.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to							
Grassland	**(18.3)**	**(23.5)**	**(15.5)**	**(19.9)**	**(20.2)**	**(20.3)**	**(19.8)**
Mineral Soils	(18.9)	(25.0)	(16.9)	(21.3)	(21.6)	(21.6)	(21.1)
Organic Soils	0.6	1.5	1.4	1.4	1.4	1.3	1.3
Forest Land Converted to							
Grassland	**16.3**	**16.3**	**15.1**	**14.8**	**14.9**	**14.9**	**14.8**
Aboveground Live Biomass	9.9	9.6	8.8	8.6	8.6	8.6	8.6
Belowground Live Biomass	2.4	2.4	2.2	2.1	2.1	2.1	2.1
Dead Wood	(0.7)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Litter	4.8	4.8	4.6	4.6	4.6	4.6	4.6
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)	(0.2)	(0.2)
Organic Soils	+	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to							
Grassland	**(4.2)**	**(31.7)**	**(22.8)**	**(18.3)**	**(18.3)**	**(18.1)**	**(17.6)**
Mineral Soils	(4.2)	(31.7)	(22.9)	(18.4)	(18.4)	(18.2)	(17.7)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to							
Grassland	**(0.2)**	**(1.4)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.8)**
Mineral Soils	(0.2)	(1.4)	(1.0)	(0.9)	(0.9)	(0.9)	(0.8)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to							
Grassland	**0.1**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.3	0.3	0.2	0.2	0.2
Aboveground Live Biomass	**9.9**	**9.6**	**8.8**	**8.6**	**8.6**	**8.6**	**8.6**
Belowground Live Biomass	**2.4**	**2.4**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**
Dead Wood	**(0.7)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**
Litter	**4.8**	**4.8**	**4.6**	**4.6**	**4.6**	**4.6**	**4.6**
Total Mineral Soil Flux	**(23.4)**	**(58.2)**	**(40.8)**	**(40.7)**	**(41.1)**	**(40.8)**	**(39.8)**
Total Organic Soil Flux	**0.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**	**1.8**
Total Net Flux	**(6.2)**	**(40.1)**	**(23.9)**	**(24.0)**	**(24.4)**	**(24.1)**	**(23.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-45: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT C)

	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to							
Grassland	**(5.0)**	**(6.4)**	**(4.2)**	**(5.4)**	**(5.5)**	**(5.5)**	**(5.4)**
Mineral Soils	(5.2)	(6.8)	(4.6)	(5.8)	(5.9)	(5.9)	(5.8)
Organic Soils	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Converted to							
Grassland	**4.4**	**4.4**	**4.1**	**4.0**	**4.1**	**4.1**	**4.0**
Aboveground Live Biomass	2.7	2.6	2.4	2.4	2.4	2.4	2.4
Belowground Live Biomass	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1

Other Lands Converted to Grassland	(1.1)	(8.6)	(6.2)	(5.0)	(5.0)	(4.9)	(4.8)
Mineral Soils	(1.2)	(8.6)	(6.3)	(5.0)	(5.0)	(5.0)	(4.8)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	+	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Mineral Soils	+	(0.4)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	+	0.1	0.1	0.1	0.1	0.1	0.1
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	2.7	2.6	2.4	2.4	2.4	2.4	2.4
Belowground Live Biomass	0.7	0.6	0.6	0.6	0.6	0.6	0.6
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Total Mineral Soil Flux	(6.4)	(15.9)	(11.1)	(11.1)	(11.2)	(11.1)	(10.9)
Total Organic Soil Flux	0.2	0.5	0.5	0.5	0.5	0.5	0.5
Total Net Flux	(1.7)	(10.9)	(6.5)	(6.6)	(6.7)	(6.6)	(6.3)

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.
+ Does not exceed 0.05 MMT C.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Grassland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of *Forest Land Converted to Grassland*, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic C stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter C stock changes for *Forest Land Converted to Grassland*. Estimates are calculated in the same way as those in the Forest Land Remaining Forest Land category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2018). There are limited data on the herbaceous grassland C stocks following conversion so default biomass estimates (IPCC 2006) for grasslands were used to estimate C stock changes (Note: litter and dead wood C stocks were assumed to be zero following conversion because no reference C density estimates exist for grasslands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass C that is lost abruptly with *Forest Land Converted to Grasslands* is estimated based on the amount of C before conversion and the amount of C following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady is reached. It was determined that using an IPCC Tier I approach that assumes all C is lost in the year of conversion for *Forest Land Converted to Grasslands* in the West and Great Plains states does not accurately characterize the transfer of C in woody biomass during abrupt or gradual land use change. To estimate this transfer of C in woody biomass, state-specific C densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of C stock changes from Forest Land Converted to Grasslands in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass C density was lost during conversion from Forest Land to Grasslands. This estimate was used to develop state-specific C density estimates for biomass, dead wood, and litter for Grasslands in the West and Great Plains states and these state-specific C densities were applied in the

compilation system to estimate the C losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are often characterized as woodlands are included in this category using FIA plot re-measurements and the methods and models described hereafter.

If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter that are not attached to live or standing dead trees at transect intersection. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). See Annex 3.13 for more information about reference C density estimates for forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for *Land Converted to Grassland* according to land use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2015 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes in mineral soils for most of the area in *Land Converted to Grassland*. C stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2019 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the

surrogate data method. Stock change estimates for 2016 to 2019 will be recalculated in future inventories when new NRI data are available.

Tier 3 Approach. Mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical[58] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

Soil organic C stock changes from 2016 to 2019 were estimated using a surrogate data method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see the Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Grassland Remaining Grassland* and Annex 3.12. This analysis includes application of the surrogate data method that is described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. As with the Tier 3 method, future Inventories will be updated with new NRI activity data when the data are made available, and the time series will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section and Annex 3.12 for organic soils. A surrogate data method is used to estimate annual C emissions from organic soils from 2016 to 2019 as described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. Estimates for 2016 to 2019 will be recalculated in future Inventories when new NRI data are available.

Uncertainty and Time-Series Consistency

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2019, there is additional uncertainty propagated through the Monte Carlo Analysis associated with a surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-46 for each subsource (i.e., biomass C stocks, mineral and organic C stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Grassland* ranges from 146 percent below to 148 percent above the 2019 stock change estimate of 23.2 MMT CO_2

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[58] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

Eq. The large relative uncertainty around the 2019 stock change estimate is partly due to large uncertainties in biomass and dead organic matter C losses with *Forest Land Conversion to Grassland*. The large relative uncertainty is also partly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with the splicing method.

Table 6-46: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Grassland* (MMT CO$_2$ Eq. and Percent)

Source	2019 Flux Estimate[a] (MMT CO$_2$ Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO$_2$ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(19.8)**	**(51.1)**	**11.5**	**-158%**	**158%**
Mineral Soil C Stocks: Tier 3	(15.0)	(46.0)	15.9	-206%	206%
Mineral Soil C Stocks: Tier 2	(6.1)	(10.4)	(1.8)	-70%	70%
Organic Soil C Stocks: Tier 2	1.3	+	2.7	-101%	101%
Forest Land Converted to Grassland	**14.8**	**4.2**	**27.0**	**-71%**	**82%**
Aboveground Live Biomass	8.6	(0.4)	19.3	-105%	123%
Belowground Live Biomass	2.1	(0.1)	4.8	-105%	127%
Dead Wood	(0.6)	(1.9)	+	-226%	106%
Litter	4.6	(0.2)	10.0	-105%	116%
Mineral Soil C Stocks: Tier 2	(0.2)	(0.4)	+	-99%	99%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-110%	110%
Other Lands Converted to Grassland	**(17.6)**	**(24.4)**	**(10.8)**	**-39%**	**39%**
Mineral Soil C Stocks: Tier 2	(17.7)	(24.5)	(10.9)	-39%	39%
Organic Soil C Stocks: Tier 2	0.1	+	0.2	-146%	146%
Settlements Converted to Grassland	**(0.8)**	**(1.1)**	**(0.5)**	**-37%**	**37%**
Mineral Soil C Stocks: Tier 2	(0.8)	(1.1)	(0.5)	-36%	36%
Organic Soil C Stocks: Tier 2	+	+	+	-293%	293%
Wetlands Converted to Grasslands	**0.2**	**(0.1)**	**0.5**	**-137%**	**137%**
Mineral Soil C Stocks: Tier 2	+	(0.1)	+	-130%	130%
Organic Soil C Stocks: Tier 2	0.2	+	0.5	-111%	111%
Total: Land Converted to Grassland	**(23.2)**	**(56.9)**	**11.1**	**-146%**	**148%**
Aboveground Live Biomass	**8.6**	**(0.4)**	**19.3**	**-105%**	**123%**
Belowground Live Biomass	**2.1**	**(0.1)**	**4.8**	**-105%**	**127%**
Dead Wood	**(0.6)**	**(1.9)**	**+**	**-226%**	**106%**
Litter	**4.6**	**(0.2)**	**10.0**	**-105%**	**116%**
Mineral Soil C Stocks: Tier 3	**(15.0)**	**(46.0)**	**15.9**	**-206%**	**206%**
Mineral Soil C Stocks: Tier 2	**(24.8)**	**(32.9)**	**(16.7)**	**-33%**	**33%**
Organic Soil C Stocks: Tier 2	**1.8**	**0.5**	**3.2**	**-76%**	**76%**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. However, there are currently no datasets to evaluate the trends. Changes in biomass and dead organic matter C stocks are assumed to be negligible with the exception of forest lands, which are included in this analysis in other grasslands. This assumption will be further explored in a future Inventory.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland* for information on QA/QC steps. Errors were found in the estimation of uncertainty due to incorrect cell references in spreadsheets. The errors were corrected through quality control review of the Inventory.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2018 on biomass, dead wood and litter C stocks in *Forest Land Converted to Grassland,* and updated estimates for mineral soils from 2016 to 2018 using additional surrogate data. As a result, *Land Converted to Grassland* has a smaller reported change in C stocks compared to the previous Inventory, estimated at 0.17 MMT CO_2 Eq. on average over the time series. This represents a 1 percent decrease in C stock changes for *Land Converted to Grassland* compared to the previous Inventory.

Planned Improvements

The amount of biomass C that is lost abruptly or the slower changes that continue to occur over a decade or longer with *Forest Land Converted to Grasslands* will be further refined in a future Inventory. The current values are estimated based on the amount of C before conversion and an estimated level of C left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of C left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter C pools. In addition, biomass C stock changes will be estimated for *Cropland Converted to Grassland*, and other land use conversions to grassland, to the extent that data are available.

An additional planned improvement for the *Land Converted to Grassland* category is to develop an inventory of C stock changes for grasslands in Alaska. Table 6-47 provides information on the amount of managed area in Alaska that is *Land Converted to Grassland*, which is as high as 54 thousand hectares in 2011.[59] Note that areas of *Land Converted to Grassland* in Alaska for 1990 to 2001 are classified as *Grassland Remaining Grassland* because land use change data are not available until 2002. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

Table 6-47: Area of Managed Land in *Land Converted to Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	9,394	9,394	0
1991	9,485	9,485	0
1992	9,691	9,691	0
1993	11,566	11,566	0
1994	13,378	13,378	0
1995	13,994	13,994	0
1996	14,622	14,622	0

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[59] All of the *Land Converted to Grassland* according to the land representation is included in the inventory from 1990 through 2001 for the conterminous United States. However, there are no data to evaluate land use change in Alaska for this time period, and so the balance of the managed area that may be converted to grassland in these years is included in *Grassland Remaining Grassland* section. This gap in land use change data for Alaska will be addressed in a future Inventory.

1997	15,162	15,162	0
1998	19,052	19,052	0
1999	19,931	19,931	0
2000	20,859	20,859	0
2001	21,968	21,968	0
2002	22,395	22,392	3
2003	22,015	22,008	7
2004	22,557	22,547	10
2005	22,460	22,447	13
2006	22,718	22,702	16
2007	22,450	22,428	21
2008	22,685	22,661	24
2009	22,608	22,581	26
2010	22,664	22,634	29
2011	22,805	22,750	54
2012	22,643	22,596	47
2013	21,472	21,439	33
2014	20,195	20,163	33
2015	20,242	20,210	33
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.8 Wetlands Remaining Wetlands (CRF Category 4D1)

Wetlands Remaining Wetlands includes all wetland in an Inventory year that had been classified as wetland for the previous 20 years, and in this Inventory the flux estimates include Peatlands and Coastal Wetlands.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under *Peatlands Remaining Peatlands*), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for *Peatlands Remaining Peatlands* consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on

site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided for rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current Inventory estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: sphagnum bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from sphagnum bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N_2O and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines.

On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.8 MMT CO_2 Eq. in 2019 (see Table 6-48 and Table 6-49) comprising 0.8 MMT CO_2 Eq. (778 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.16 kt) of CH_4 and 0.0005 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2019 were about 2.7 percent less than total emissions in 2018.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.7 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2019. Carbon dioxide emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.7 and 1.3 MMT CO_2 across the time series, and

these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series. Nitrous oxide emissions showed a decreasing trend from 1990 until 1995, followed by an increasing trend through 2001. Nitrous oxide emissions decreased between 2001 and 2006, followed by a leveling off between 2008 and 2010, and a general decline between 2011 and 2019. Methane emissions decreased from 1990 until 1995, followed by an increasing trend through 2000, a period of fluctuation through 2010, and a general decline between 2010 and 2019 (emissions rose slightly from 2016 to 2017 but resumed the downward trend since).

Table 6-48: Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq.)

Gas	1990		2005		2015	2016	2017	2018	2019
CO₂	1.1		1.1		0.8	0.8	0.8	0.7	0.8
Off-site	1.0		1.0		0.7	0.7	0.7	0.7	0.7
On-site	0.1		0.1		+	+	0.1	0.1	0.1
CH₄ (On-site)	+		+		+	+	+	+	+
N₂O (On-site)	+		+		+	+	+	+	+
Total	1.1		1.1		0.8	0.7	0.8	0.8	0.8

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 6-49: Emissions from *Peatlands Remaining Peatlands* (kt)

Gas	1990		2005		2015	2016	2017	2018	2019
CO₂	1,055		1,101		755	733	829	795	778
Off-site	985		1,030		706	686	774	744	727
On-site	70		71		49	47	55	51	50
CH₄ (On-site)	+		+		+	+	+	+	+
N₂O (On-site)	+		+		+	+	+	+	+

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.
+ Does not exceed 0.5 kt

Methodology

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from *Peatlands Remaining Peatlands* were calculated by apportioning the annual weight of peat produced in the United States (Table 6-50) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1995 through 2017; USGS 2018; USGS 2020). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the *Alaska's Mineral Industry* report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-51). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[60] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015); and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2019 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic C were estimated by multiplying the area of peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over time the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; in 2018, imports of sphagnum moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports (USGS 2018). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

Table 6-50: Peat Production of Lower 48 States (kt)

Type of Deposit	1990		2005		2015	2016	2017	2018	2019
Nutrient-Rich	595.1		657.6		405.0	388.1	423.3	416.7	423.0
Nutrient-Poor	55.4		27.4		50.1	52.9	74.7	62.3	47.0
Total Production	**692.0**		**685.0**		**455.0**	**441.0**	**498.0**	**479.0**	**470.0**

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2020) *Mineral Commodity Summaries: Peat (2020).*

Table 6-51: Peat Production of Alaska (Thousand Cubic Meters)

	1990		2005		2015	2016	2017	2018	2019
Total Production	49.7		47.8		93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014).*

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[60] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] sphagnum moss are extensive" (USGS 2008).

On-site CO$_2$ Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[61] The area of land managed for peat extraction in the lower 48 states of the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-52. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO$_2$ emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from *Peatlands Remaining Peatlands* in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-53. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-52: Peat Production Area of Lower 48 States (Hectares)

	1990[a]		2005		2015	2016	2017	2018	2019
Nutrient-Rich	5,951		6,576		4,050	3,881	4,233	4,167	4,230
Nutrient-Poor	554		274		501	529	747	623	470
Total Production	**6,920**		**6,850**		**4,550**	**4,410**	**4,980**	**4,790**	**4,700**

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.
Sources: Calculated using peat production values in Table 6-50, an assumed yield of 100 metric tons per hectare per year.

Table 6-53: Peat Production Area of Alaska (Hectares)

	1990		2005		2015	2016	2017	2018	2019
Nutrient-Rich	0		0		0	0	0	0	0
Nutrient-Poor	286		104		209	201	333	212	212
Total Production	**286**		**104**		**209**	**201**	**333**	**212**	**212**

Sources: Calculated using peat production values in Table 6-51, an assumed yield of 100 metric tons per hectare per year.

On-site N$_2$O Emissions

IPCC (2006) suggests basing the calculation of on-site N$_2$O emission estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO$_2$ emissions methodology above details the calculation of area data from production data. In order to

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[61] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

estimate N_2O emissions, the area of nutrient-rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2013).

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the area of *Peatlands Remaining Peatlands* was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-54 for the calculated area of ditches and drained land.

Table 6-54: Peat Production (Hectares)

	1990		2005		2015	2016	2017	2018	2019
Lower 48 States									
Area of Drained Land	6,574		6,508		4,323	4,190	4,731	4,551	4,465
Area of Ditches	346		343		228	221	249	240	235
Total Production	**6,920**		**6,850**		**4,550**	**4,410**	**4,980**	**4,790**	**4,700**
Alaska									
Area of Drained Land	272		99		198	191	317	202	202
Area of Ditches	14		5		10	10	17	11	11
Total Production	**286**		**104**		**209**	**201**	**333**	**212**	**212**

Sources: Calculated using peat production values in Tables Table 6-50 and Table 6-51, an assumed yield of 100 metric tons per hectare per year, and an assumed value of 5 percent ditch area.

Uncertainty and Time-Series Consistency

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from *Peatlands Remaining Peatlands* for 2019, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.
- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-55. Carbon dioxide emissions from *Peatlands Remaining Peatlands* in 2019 were estimated to be between 0.7 and 0.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2019 emission estimate of 0.8 MMT CO_2 Eq. Methane emissions from *Peatlands Remaining Peatlands* in 2019 were estimated to be between 0.002 and 0.007 MMT CO_2 Eq. This indicates a range of 59 percent below to 78 percent above the 2019 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from *Peatlands Remaining Peatlands* in 2017 were estimated to be between 0.0003 and 0.0009 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 56 percent below to 56 percent above the 2019 emission estimate of 0.0006 MMT CO_2 Eq.

Table 6-55: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from *Peatlands Remaining Peatlands* (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.8	0.7	0.9	-16%	16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-59%	78%
Peatlands Remaining Peatlands	N_2O	+	+	+	-56%	56%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The emission estimates for *Peatlands Remaining Peatlands* were updated for 2019 using the Peat section of the *Mineral Commodity Summaries 2018, Mineral Commodity Summaries 2019* and *Mineral Commodity Summaries 2020*. The 2018 edition updated 2013 data and the 2019 edition updated 2014 data for the lower 48 states. The 2020 edition updated 2017 data and provided peat type production estimates for 2018 and 2019. Although Alaska peat production data for 2017 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013, 2014, 2015, 2016, 2017, 2018, and 2019 values were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated data are available for the next inventory cycle, this will result in a recalculation in the next Inventory report.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from *Peatlands Remaining Peatlands*, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

Efforts will also be made to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued.

The implied emission factors will be calculated and included in this chapter for future Inventories. The N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations, so estimating the

implied emission factor per total land area is not appropriate and are not generated in the CRF tables. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification.

The *2006 IPCC Guidelines* do not cover all wetland types; they are restricted to peatlands drained and managed for peat extraction, conversion to flooded lands, and some guidance for drained organic soils. They also do not cover all of the significant activities occurring on wetlands (e.g., rewetting of peatlands). Since this Inventory only includes *Peatlands Remaining Peatlands*, additional wetland types and activities found in the *2013 IPCC Supplement* will be reviewed to determine if they apply to the United States. For those that do, available data will be investigated to allow for the estimation of greenhouse gas fluxes in future inventory years.

Coastal Wetlands Remaining Coastal Wetlands

This Inventory recognizes Wetlands as a "land-use that includes land covered or saturated for all or part of the year, in addition to areas of lakes, reservoirs, and rivers." Consistent with ecological definitions of wetlands,[62] the United States has historically included under the category of Wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation.

Guidance on quantifying greenhouse gas emissions and removals on Coastal Wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*), which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon and the gain-loss method for biomass and DOM. Presently, this Inventory does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation.

The United States recognizes both Vegetated Wetlands and Unvegetated Open Water as Coastal Wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in Vegetated Coastal Wetlands and does not occur in Unvegetated Open Water Coastal Wetlands. The United States takes the additional step of recognizing that stock losses occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands.

This Inventory includes all privately-owned and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores on the conterminous United States, but does not include *Coastal Wetlands Remaining Coastal Wetlands* in Alaska or Hawaii. Seagrasses are not currently included within the Inventory due to insufficient data on distribution, change through time and carbon (C) stocks or C stock changes as a result of anthropogenic influence.

Under the *Coastal Wetlands Remaining Coastal Wetlands* category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*,
2) Carbon stock changes on *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*,
3) Carbon stock changes on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*, and
4) *Nitrous Oxide Emissions from Aquaculture in Coastal Wetlands*.

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[62] See <https://water.usgs.gov/nwsum/WSP2425/definitions.html>; accessed October 2020.

Vegetated coastal wetlands hold C in all five C pools (i.e., aboveground, belowground, dead organic matter [DOM; dead wood and litter], and soil) though typically soil C and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). Vegetated Coastal Wetlands are net accumulators of C as soils accumulate C under anaerobic soil conditions and in plant biomass. Emissions from soil C and biomass stocks occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands (e.g., when Vegetated Coastal Wetlands are lost due to subsidence, channel cutting through Vegetated Coastal Wetlands), but are still recognized as Coastal Wetlands in this Inventory. These C stock losses resulting from conversion to Unvegetated Open Water Coastal Wetlands can cause the release of many years of accumulated soil C, as well as the standing stock of biomass C. Conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands initiates the building of C stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for CH_4 emissions, coastal wetlands in salinity conditions less than half that of sea water are sources of CH_4 as result of slow decomposition of organic matter under lower salinity brackish and freshwater, anaerobic conditions. Conversion of Vegetated Coastal Wetlands to or from Unvegetated Open Water Coastal Wetlands do not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the N derived from consumption of the applied food stock that is then excreted as N load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic N loading from the watershed and atmospheric deposition, these emissions are not reported here to avoid double-counting of indirect N_2O emissions with the Agricultural Soils Management, Forest Land and Settlements categories.

The *Wetlands Supplement* provides methodologies for estimating C stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, C stock changes from mangroves may be reported under the Forest Land category or under Coastal Wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the Forest Land category. Mangrove forests that are less than 5 m are reported under Coastal Wetlands. All other non-drained, intact coastal marshes are intended to be reported under Coastal Wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6, and as such estimates of C stock changes, emissions of CH_4, and emissions of N_2O from aquaculture are included in this Inventory. At the present stage of inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[63] with NRI, FIA and NLDC data used to compile the Land Representation. However, a check was undertaken to confirm that Coastal Wetlands recognized by C-CAP represented a subset of Wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-56. *Coastal Wetlands Remaining Coastal Wetlands* are generally a net C sink, with the fluxes ranging from -3.7 to -4.8 MMT CO_2 Eq. across the majority of the time series, however, between 2006 and 2010 they were a net source of emissions (ranging from of 5.2 to 5.5 MMT CO_2 Eq.), resulting from large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-56). Recognizing removals of CO_2 to soil of 10.2 MMT CO_2 Eq. and CH_4 emissions of 3.8 MMT CO_2 Eq. in 2019, *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are a net sink of 6.4 MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as *Vegetated Coastal Wetlands Converted to Unvegetated Coastal* Wetlands, drive an emission of 1.5 MMT CO_2 Eq. primarily from soils. Building of new wetlands from open water, recognized as *Unvegetated Coastal Wetlands Converted to Vegetated Coastal*, results each year in removal of 0.1 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.01 to 0.2 MMT CO_2 Eq. In all, *Coastal Wetlands* are a net sink of 4.8 MMT CO_2 Eq. in 2019.

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[63] See <https://coast.noaa.gov/digitalcoast/tools/lca.html>; accessed August 2020.

Table 6-56: Emissions and Removals from *Coastal Wetlands Remaining Coastal Wetlands* (MMT CO$_2$ Eq.)

Land Use/Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(6.5)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**
Biomass C Flux	(+)	0.1	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
Soil C Flux	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Net CH$_4$ Flux	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N$_2$O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass C Flux	**+**	**0.1**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(8.5)**	**(7.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**
Total CH$_4$ Flux	**3.7**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**
Total N$_2$O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Flux	**(4.6)**	**(3.7)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* comprised of tidally influenced palustrine emergent marsh (659,178 ha), palustrine scrub shrub (132,934 ha) and estuarine emergent marsh (1,894,854 ha), estuarine scrub shrub (93,555 ha) and estuarine forest (195,646 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in Texas, do not attain the height status to be recognized as Forest Land, and are therefore always classified within Vegetated Coastal Wetlands. *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are found in cold temperate (53,976 ha), warm temperate (895,976 ha), subtropical (1,963,565 ha) and Mediterranean (62,649 ha) climate zones.

Soils are the largest C pool in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, reflecting long-term removal of atmospheric CO$_2$ by vegetation and transfer into the soil pool in the form of decaying organic matter. Soil C emissions are not assumed to occur in coastal wetlands that remain vegetated. This Inventory includes changes in biomass C stocks along with soils. Methane emissions from decomposition of organic matter in anaerobic conditions are significant at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of C stock changes or CH$_4$ emissions.

Table 6-57 through Table 6-59 below summarize nationally aggregated biomass and soil C stock changes and CH$_4$ emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Intact *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* hold a total biomass C stock of 35.9 MMT C. Removals from

biomass C stocks in 2019 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-57 and Table 6-58). Carbon dioxide emissions from biomass in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* between 2002 and 2011 are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large C stock within the top 1 meter of soil (estimated to be 800 MMT C) to which C accumulated at a rate of 10.2 MMT CO_2 Eq. (2.8 MMT C) in 2019, a value that has remained relatively constant across the reporting period. For *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, methane emissions of 3.8 of MMT CO_2 Eq. (153 kt CH_4) in 2019 (Table 6-59) offset C removals resulting in a net removal of 6.4 MMT CO_2 Eq. in 2019; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of Vegetated Coastal Wetlands through human activities slowed considerably in the 1970s and the current annual rates of C stock change and CH_4 emissions are relatively constant over time.

Table 6-57: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2015	2016	2017	2018	2019
Biomass Flux	(+)		0.1		(0.05)	(0.05)	(0.05)	(0.05)	(0.05)
Soil Flux	(10.2)		(10.2)		(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Total C Stock Change	**(10.2)**		**(10.2)**		**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Table 6-58: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT C)

Year	1990		2005		2015	2016	2017	2018	2019
Biomass Flux	(+)		+		(+)	(+)	(+)	(+)	(+)
Soil Flux	(2.8)		(2.8)		(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Total C Stock Change	**(2.8)**		**(2.8)**		**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.05 MMT C.

Table 6-59: CH_4 Emissions from *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq. and kt CH_4)

Year	1990		2005		2015	2016	2017	2018	2019
Methane Emissions (MMT CO_2 Eq.)	3.7		3.8		3.8	3.8	3.8	3.8	3.8
Methane Emissions (kt CH_4)	149		151		152	153	153	153	153

Methodology

The following section includes a description of the methodology used to estimate changes in biomass C stocks, soil C stocks and emissions of CH_4 for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Dead organic matter is not calculated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since it is assumed to be in steady state (IPCC 2014).

Biomass Carbon Stock Changes

Above- and below ground biomass C Stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 (new to this year's inventory) NOAA C-CAP surveys (NOAA OCM

2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2019 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-60). Biomass is not sensitive to soil organic content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017;

Table 6-61). Root to shoot ratios from the *Wetlands Supplement* (Table 6-62; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass C stock changes per year for wetlands remaining wetlands were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-60: Area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands, Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*, and *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (ha)

Year	1990	2005	2015	2016	2017	2018	2019
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,985,512	2,988,258	2,971,102	2,972,368	2,973,634	2,974,900	2,976,166
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	953	1,775	2,406	2,406	2,406	2,406	2,406

Table 6-61: Aboveground Biomass Carbon Stocks for *Vegetated Coastal Wetlands* (t C ha^{-1})

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	3.05	3.10	17.83	3.44
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017).

Table 6-62: Root to Shoot Ratios for *Vegetated Coastal Wetlands*

	Climate Zone			
Wetland Type	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63
Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	1.15	1.15	0.96	3.63
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

All values from IPCC (2014).

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* for both mineral and organic soils. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-63; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016).

Tier 2 level estimates of soil C removals associated with annual soil C accumulation on managed *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* were developed with country-specific soil C removal factors multiplied by activity data of land area for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on an annual basis. To estimate soil C stock changes, no differentiation is made between organic and mineral soils since currently no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-63: Annual Soil Carbon Accumulation Rates for *Vegetated Coastal Wetlands* (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.01	1.54	0.45	0.85
Palustrine Emergent Wetland	1.01	1.54	0.45	0.85
Estuarine Forested Wetland	1.01	0.82	0.87	0.85
Estuarine Scrub/Shrub Wetland	1.01	0.82	1.09	0.85
Estuarine Emergent Wetland	2.17	0.82	1.09	0.85

All data from Lu and Megonigal (2017)[64]

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and as a result CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty and Time-Series Consistency

Underlying uncertainties in the estimates of soil and biomass C stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil C stocks, biomass C stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* include differentiation of palustrine and estuarine community classes, which determines the soil C stock and CH_4 flux applied. Uncertainties for soil and biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying

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[64] See <https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public>; accessed October 2020.

approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-64 and Table 6-65 for each subsource (i.e., soil C, biomass C and CH_4 emissions). The combined uncertainty across all subsources is +/-36.6 percent, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 1990, the total flux was -6.5 MMT CO_2 Eq., with lower and upper estimates of -8.8 and -4.1 MMT CO_2 Eq. In 2019, the total flux was -6.4 MMT CO_2 Eq., with lower and upper estimates of -8.7 and -4.1 MMT CO_2 Eq.

Table 6-64: IPCC Approach 1 Quantitative Uncertainty Estimates for C Stock Changes and CH_4 Emissions occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* in 1990 (MMT CO_2 Eq. and Percent)

Source	Gas	1990 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.01)	(0.01)	(0.01)	-24.1%	24.1%
Soil C Stock Change	CO_2	(10.2)	(12.0)	(8.4)	-17.8%	17.8%
CH_4 emissions	CH_4	3.7	2.6	4.8	-29.8%	29.8%
Total Flux		**(6.5)**	**(8.8)**	**(4.1)**	**-36.6%**	**36.6%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. + Absolute value does not exceed 0.05 MMT CO_2 Eq.

Table 6-65: IPCC Approach 1 Quantitative Uncertainty Estimates for C Stock Changes and CH_4 Emissions occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* in 2019 (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(+)	-24.1%	24.1%
Soil C Stock Change	CO_2	(10.2)	(12.0)	(8.4)	-17.8%	17.8%
CH_4 emissions	CH_4	3.8	2.7	5.0	-29.8%	29.8%
Total Flux		**(6.4)**	**(8.7)**	**(4.1)**	**-36.6%**	**36.6%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding. + Absolute value does not exceed 0.05 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil C stock datasets have been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads who reviewed summary tables against reviewed sources. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in this Inventory. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass C stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

As part of the addition of a 2016 C-CAP dataset, the previous datasets (1996, 2001, 2006, and 2011) were refined and reanalyzed using the improved methods, software and techniques that were used for the 2016 dataset to create the most accurate and representative product. Additionally, coastal wetland areas were calculated at the state/territory level and summed based on climate zone to the national level. This change was implemented so that emissions and removals could be calculated at the state/territory level.

The addition of the 2016 C-CAP dataset resulted in changes in area calculations for 1990 to 1995 and 2011 to 2018. Previously, the average change across all C-CAP time periods (1996 through 2011) was used for years outside of the C-CAP dataset. For 1990 to 1995 and 2017 to 2019, the C-CAP change data for the period closest to a given year were used instead of the average change value. This is because there was largescale wetland loss between 2001 and 2006 due to major hurricanes in 2005, which resulted in elevated wetland loss that was not consistent across years. For 1990 through 1995, the 1996 to 2000 C-CAP change data were used, and the 2011 to 2016 C-CAP change data were used for 2017 through 2019. This resulted in the following area changes in 1990 (64,848 ha increase in palustrine emergent marsh, 626 ha increase in palustrine scrub shrub marshes, 28,419 increase in estuarine emergent marshes, 8,140 ha decrease in estuarine scrub shrub marshes, and 14,347 ha increase in estuarine forested wetlands) and 2018 (54,438 ha increase in palustrine emergent marsh, 9,320 ha decrease in palustrine scrub shrub marshes, 57,966 increase in estuarine emergent marshes, 4,388 ha decrease in estuarine scrub shrub marshes, and 3,513 ha increase in estuarine forested wetlands).

Although this change does not affect the area or flux calculations presented here, a new organic soil geospatial layer was derived from CONUS distributions of histosols in the USDA's Soil Survey Geographic Database (SSURGO). The dataset is complete except for a large portion of the Florida Everglades did not contain data. Incorporating this new dataset resulted in a large change in extents between organic and mineral soils, with less area of organic soils nationally than reported previously.

A corrigendum was published by Byrd et al. (2020) for non-forested, emergent wetland aboveground biomass values initially presented in Byrd et al. (2018). The updated analyses resulted in increases in aboveground biomass carbon stocks across all wetland types and climate zones (except for the Puget Sound, which had a 0.1 t C ha^{-1} decrease); the average aboveground biomass increased from 1.93 to 3.02 t C ha^{-1}.

Belowground biomass carbon stock changes are now included for coastal wetlands and result in increased biomass C stock fluxes. These values are based on Tier 2 root to shoot ratios from the *Wetlands Supplement* (IPCC 2014).

These recalculations did not result in a net change in removals for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*; however, within individual subsource categories soil C accumulation increased by 0.3 MMT CO_2 Eq. in both 1990 and 2018 from -9.9 to -10.2 MMT CO_2 Eq., and net biomass carbon stocks increased by 0.01 MMT CO_2 Eq. in 1990 and changed towards an emission of 0.2 MMT CO_2 Eq. in 2018 as compared to the previous Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stock and biomass estimates for coastal wetlands.[65] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent updated changes in soil C stocks for estuarine emergent wetlands.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass C stocks into the *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands is a source of emissions from soil, biomass, and DOM C stocks. An estimated 1,488 ha of Vegetated Coastal Wetlands were converted to Unvegetated Open Water Coastal Wetlands in 2019, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquifer extraction. Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The most recent land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. Land Representation is recognized as falling under the Wetlands category within this Inventory. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This Inventory adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland C loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized C is immediately returned to the atmosphere (as assumed for terrestrial land use categories), rather than redeposited in long-term C storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland C based upon the geomorphic setting of the depositional environment.

In 2019, there were 1,488 ha of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT

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[65] See <https://serc.si.edu/coastalcarbon>; accessed October 2020.

CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, while DOM C stock loss was present it was minimal (Table 6-60, Table 6-66, and Table 6-67). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-60).

Table 6-66: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2015	2016	2017	2018	2019
Biomass Flux	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+		+		+	+	+	+	+
Soil Flux	1.7		2.5		1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**		**2.6**		**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

Note: Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Table 6-67: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT C)

Year	1990		2005		2015	2016	2017	2018	2019
Biomass Flux	+		+		+	+	+	+	+
Dead Organic Matter Flux	+		+		+	+	+	+	+
Soil Flux	0.5		0.7		0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**		**0.7**		**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

Note: Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.05 MMT C.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*.

Biomass Carbon Stock Changes

Biomass C stock changes for palustrine and estuarine marshes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys; the latter is new to this analysis. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2019 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass C stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass C stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[66]; Table 6-61). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open

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[66] See <https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public>; accessed October 2020.

water results in emissions of all biomass C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 to 2019 time series. Conversion to open water results in emissions of all DOM C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM C stock.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. Country-specific soil C stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis demonstrated that it was not justified to stratify C stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil C stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil C loss with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands is assumed to affect soil C stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil and biomass C stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from

those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Uncertainty estimates are presented in Table 6-69 and Table 6-69 for each subsource (i.e., soil C, biomass C, and DOM emissions). The combined uncertainty across all subsources is +/-32.0 percent, which is driven by the uncertainty in the soil C estimates. In 1990, the total C flux was 1.8 MMT CO_2 Eq., with lower and upper estimates of 1.2 and 2.3 MMT CO_2 Eq. In 2019, the total C flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-68: Approach 1 Quantitative Uncertainty Estimates for CO₂ Flux Occurring within *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* **in 1990 (MMT CO₂ Eq. and Percent)**

Source	1990 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.07	0.06	0.09	-24.1%	24.1%
Dead Organic Matter C Stock	+	+	+	-25.8%	25.8%
Soil C Stock	1.7	1.4	2.0	-15.0%	15.0%
Total Flux	**1.8**	**1.2**	**2.3**	**-32.0%**	**32.0%**

Note: Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.0005 MMT CO_2 Eq.

Table 6-69: Approach 1 Quantitative Uncertainty Estimates for CO₂ Flux Occurring within *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* **in 2019 (MMT CO₂ Eq. and Percent)**

Source	2019 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	24.1%
Dead Organic Matter C Stock	0.0005	+	0.001	-25.8%	25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**32.0%**

Note: Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.0005 MMT CO_2 Eq.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil C stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates

against primary scientific literature. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in the Inventory. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014) Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

For a full discussion on the recalculations implemented for this Inventory, please see the Recalculations section for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands.* For *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Wetlands*, these changes resulted in a reduction of 3,107 and 3,340 ha of vegetated coastal wetlands converted to unvegetated open water coastal wetlands in 1990 and 2018, respectively. In comparison to the previous Inventory, this decreased emissions by 3.1 and 3.3 MMT CO_2 Eq. (64.0 and 68.2 percent) in 1990 and 2018, respectively. Between 2006 and 2010, the period with the largest area conversion, an increase in 1,664 ha per year occurred (from 9,709 to 11,373 ha for the previous and current Inventories, respectively), resulting in a 1.7 and 0.4 MMT CO_2 Eq. increase in soil and biomass C emissions, respectively (17 and 496 percent); DOM emissions decreased by 0.0001 MMT CO_2 Eq. (3.6 percent). The large increase in biomass emissions is driven by the incorporation of belowground biomass in addition to updates to the C-CAP dataset; the small change in DOM emissions reflects the minimal reduction in the areal extent of estuarine forested wetlands mapped with C-CAP recalculations.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the US. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil C returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the inventory.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in the 6 Land Representation section, is recognized as Coastal Wetlands within this Inventory. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and

then replaced by wetland plants. Biomass, DOM and soil C accumulation on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* begins with vegetation establishment.

Within the United States, conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands* is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetlands restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2019, 2,407 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-59). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-70 and Table 6-71). The soil C stock has increased during the Inventory's reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM C stock increases are present they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2019), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of *Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-70: CO₂ Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT CO₂ Eq.)

Year	1990	2005	2015	2016	2017	2018	2019
Biomass C Flux	(0.04)	(0.08)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Total C Stock Change	**(0.04)**	**(0.09)**	**(0.11)**	**(0.11)**	**(0.11)**	**(0.11)**	**(0.11)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.005 MMT CO₂ Eq.

Table 6-71: CO₂ Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2015	2016	2017	2018	2019
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.005 MMT C.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks, and CH_4 emissions for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass C stock changes for palustrine and estuarine marsh vegetation are presented for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* on lands

below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2019 from these datasets (Table 6-58). C-CAP provides peer reviewed country-level mapping of coastal wetland distribution, including conversion to and from open water. Biomass C stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-61; Byrd et al. 2017; Byrd et al., 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[67];

Table 6-61). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to Vegetated Coastal Wetlands results in the establishment of a standing biomass C stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years*.* Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2019 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass C stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil C stock changes are estimated for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*. Country-specific soil C removal factors associated with soil C accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). Soil C stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil C stock change no differentiation is made for soil type (i.e., mineral, organic). Soil C removal factors were developed from literature references that provided soil C removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-63 for values).

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[67] See <https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public>; accessed October 2020.

Tier 2 level estimates of C stock changes associated with annual soil C accumulation in Vegetated Coastal Wetlands were developed using country-specific soil C removal factors multiplied by activity data on Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil and biomass C stock changes include uncertainties associated with country-specific (Tier 2) literature values of these C stocks and assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al. 2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-62), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-73 and Table 6-77 for each subsource (i.e., soil C, biomass C and DOM emissions). The combined uncertainty across all subsources is ±33.4 percent. In 1990, the total C flux was -0.04 MMT CO_2 Eq., with lower and upper estimates of -0.06 and -0.03 MMT CO_2 Eq. In 2019, the total C flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.07 MMT CO_2 Eq.

Table 6-72: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes Occurring within *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* in 1990 (MMT CO$_2$ Eq. and Percent)

Source	1990 Flux Estimate (MMT CO$_2$ Eq.)	Uncertainty Range (MMT CO$_2$ Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.4)	(0.05)	(0.03)	-20.0%	20.0%
Dead Organic Matter C Stock Flux	(+)	(+)	(+)	-25.8%	25.8%
Soil C Stock Flux	(0.003)	(0.003)	(0.005)	-17.8%	17.8%
Total Flux	**(0.04)**	**(0.06)**	**(0.03)**	**-33.4%**	**33.4%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.
+ Absolute value does not exceed 0.0005 MMT CO_2 Eq.

Table 6-73: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes Occurring within *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* in 2019 (MMT CO₂ Eq. and Percent)

Source	2019 Flux Estimate (MMT CO₂ Eq.)	Uncertainty Range (MMT CO₂ Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.1)	(0.08)	-20.0%	20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	25.8%
Soil C Stock Flux	(0.007)	(0.008)	(0.005)	-17.8%	17.8%
Total Flux	**(0.1)**	**(0.1)**	**(0.07)**	**-33.4%**	**33.4%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass C reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the Coastal Wetland Inventory team leads before inclusion in the inventory. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH₄ emissions are constant with conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands*.

Recalculations Discussion

For discussion on recalculations implemented for this Inventory, please see the Recalculations section for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. For *Unvegetated Open Water Coastal Waters Converted to Vegetated Coastal Wetlands*, these changes resulted in a decrease of 541 ha of unvegetated coastal wetlands converted to vegetated coastal wetlands and an increased removal of 0.02 MMT CO₂ Eq. (50 percent) in 1990 and a decrease of 913 ha of unvegetated coastal wetlands converted to vegetated coastal wetlands and an increased removal of 0.09 MMT CO₂ Eq. (450 percent) in 2018, when compared to the 2020 NIR submission.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of published data quantifying soil C stock and biomass in coastal wetlands. Reference values for soil and biomass C stocks will be updated as new data emerge. Refined error analysis combining land cover change, soil and biomass C stock estimates will be updated at those times.

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data

harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the inventory.

N$_2$O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N$_2$O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N$_2$ gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N$_2$O emissions increasing from 0.1 in 1990 to upwards of 0.2 MMT CO$_2$ Eq. between 1992 and 2010, and reducing again to 0.1 MMT CO$_2$ Eq. between 2015 and 2019 (Table 6-74). Aquaculture production data were updated through 2017; data through 2019 are not yet available and in this analysis are held constant with 2017 emissions of 0.1 MMT CO$_2$ Eq. (0.5 Kt N$_2$O).

Table 6-74: N$_2$O Emissions from Aquaculture in Coastal Wetlands (MMT CO$_2$ Eq. and kt N$_2$O)

Year	1990		2005		2015	2016	2017	2018	2019
Emissions (MMT CO$_2$ Eq.)	0.1		0.2		0.1	0.1	0.1	0.1	0.1
Emissions (kt N$_2$O)	0.4		0.6		0.5	0.5	0.5	0.5	0.5

Methodology

The methodology to estimate N$_2$O emissions from Aquaculture in Coastal Wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2020), from which activity data for this analysis is derived.[68] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N$_2$O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N$_2$O emissions from aquaculture is not sensitive to salinity using IPCC approaches and as such the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N$_2$O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N$_2$O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N$_2$O emissions.

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[68] See <https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2018-report>; accessed October 2020.

Uncertainty and Time-Series Consistency

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-75 and Table 6-76 for N_2O emissions. The combined uncertainty is ±116 percent. In 1990, the total flux was 0.1 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.28 MMT CO_2 Eq. In 2019, the total flux was 0.1 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.31 MMT CO_2 Eq.

Table 6-75: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 1990 (MMT CO_2 Eq. and Percent)

Source	1990 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.1	0.00	0.28	-116%	116%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Table 6-76: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2019 (MMT CO_2 Eq. and Percent)

Source	2019 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.1	0.00	0.31	-116%	116%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The Coastal Wetlands Inventory team consulted with the Coordinating Lead Authors of the Coastal Wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

A NOAA report was released in 2020 that contains updated fisheries data through 2017 (National Marine Fisheries Service 2020). The new values were applied for 2015, 2016, and 2017 and the 2017 value was applied in 2018 and

2019. This resulted in an increase of N_2O emissions by 0.01 MMT CO_2 Eq. (0.03 kt N_2O), a 7.4 percent increase, for 2018 compared to the previous Inventory.

6.9 Land Converted to Wetlands (CRF Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land Converted to Vegetated Coastal Wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. All other land categories (i.e., Forest Land, Cropland, Grassland, Settlements and Other Lands) are identified as having some area converting to Vegetated Coastal Wetlands. Between 1990 and 2019 the rate of annual transition for *Land Converted to Vegetated Coastal Wetlands* ranged from 0 to 2,650 ha per year, depending on the type of land converted.[69] Conversion rates from Forest Land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[70] Little to no conversion of Cropland, Grassland, Settlement, or Other Lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.

At the present stage of Inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the Land Representation (NOAA OCM 2020).

In this Inventory, biomass, dead organic material (DOM) and soil C stock changes as well as CH_4 emissions are quantified as a result of the land use conversion to coastal wetlands and the land is assumed to be held in this category for up to 20 years after which it is classified as *Coastal Wetlands Remaining Coastal Wetlands*. Estimates of emissions and removals are based on emission factor data that have been applied to assess changes in each respective flux for *Land Converted to Vegetated Coastal Wetlands*. Following conversion to Vegetated Coastal Wetlands, it is assumed there is a loss of biomass C stocks from the converted Forest Land, Cropland and Grassland and as well as the loss of DOM C stocks from Forest Land. Converted lands are held in this land category for up to 20 years and the assumption is that the C stock losses from biomass and DOM all occur in the year of conversion. There are no soil C losses from land use conversion. Carbon stock increases in coastal wetlands as a result of gains in plant biomass and DOM on these converted lands are also included during the year of transition even though the entire C stock accrual takes many years to occur. Soil C accumulation and CH_4 emissions are quantified using an annual rate in this Inventory and thus are occurring over the period under which lands are held in this category; therefore, the soil C removals and CH_4 emissions presented for a given year include the cumulative removals/emissions for the new area that was converted during that year and the area held in this category for the prior 19 years. At salinities less than half that of seawater, the transition from upland dry soils to wetland soils results in CH_4 emissions. The United States calculates emissions and removals based upon stock change.

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[69] Data from C-CAP; see <https://coast.noaa.gov/digitalcoast/tools/>. Accessed October 2020.

[70] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the Inventory.

Conversion to coastal wetlands resulted in a biomass C stock loss of 0.1 MMT CO_2 Eq. (0.03 MMT C) in 2019 (Table 6-77 and Table 6-78). Loss of forest biomass through conversion of Forest Lands to Vegetated Coastal Wetlands is the primary driver behind biomass C stock change being a source rather than a sink across the time series. Conversion of Cropland, Grassland, Settlement and Other Lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.02 MMT CO_2 Eq. (0.006 MMT C) in 2019 (Table 6-77 and Table 6-78), which is driven by the loss of DOM when Forest Land is converted to Vegetated Coastal Wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of Cropland, Grassland, Settlement and Other Land results in a net increase in DOM. Once Tier 1 or 2 DOM values are collated and accounted for in estuarine and palustrine scrub shrub coastal wetlands and estuarine forested wetlands (in climates other than subtropical), the carbon emissions will decrease. Across all time periods, soil C accumulation resulting from *Lands Converted to Vegetated Coastal Wetlands* is a carbon sink and has ranged between -0.2 and -0.3 MMT CO_2 Eq. (-0.05 and -0.07 MMT C; Table 6-77 and Table 6-78). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (7.1 kt CH_4) in 2019 (Table 6-79). Methane emissions due to the conversion of *Lands to Vegetated Coastal Wetlands* are largely the result of Forest Land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2001 (0.2 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels.

Table 6-77: Net CO₂ Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT CO₂ Eq.)

Land Use/Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.48**	**0.47**	**(0.03)**	**(0.02)**	**(0.01)**	**(0.00)**	**0.01**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.09	0.09	0.02	0.02	0.02	0.02	0.02
Soil C Stock	(0.23)	(0.24)	(0.19)	(0.18)	(0.17)	(0.16)	(0.15)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.09**	**0.09**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.20)**	**(0.19)**	**(0.18)**	**(0.18)**	**(0.17)**
Total Flux	**0.45**	**0.44**	**(0.06)**	**(0.05)**	**(0.04)**	**(0.03)**	**(0.02)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.
+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Table 6-78: Net CO₂ Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT C)

Land Use/Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)

Land Use/Carbon Pool	1990		2005		2015	2016	2017	2018	2019
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**		**0.13**		**(0.01)**	**(0.01)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	0.17		0.17		0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03		0.02		0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)		(0.06)		(0.05)	(0.05)	(0.05)	(0.04)	(0.04)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**		**(+)**		**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**		**(0.01)**		**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**		**(+)**		**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)		(+)		(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**		**0.16**		**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Dead Organic Matter Flux	**0.03**		**0.02**		**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**		**(0.07)**		**(0.06)**	**(0.05)**	**(0.05)**	**(0.05)**	**(0.05)**
Total Flux	**0.12**		**0.12**		**(0.02)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

+ Absolute value does not exceed 0.005 MMT C.

Table 6-79: CH$_4$ Emissions from *Land Converted to Vegetated Coastal Wetlands* (MMT CO$_2$ Eq. and kt CH$_4$)

Land Use/Carbon Pool	1990		2005		2015	2016	2017	2018	2019
Cropland Converted to Vegetated Coastal Wetlands									
Methane Emissions (MMT CO$_2$ Eq.)	+		+		+	+	+	+	+
Methane Emissions (kt CH$_4$)	+		0.01		0.03	0.04	0.04	0.04	0.04
Forest Land Converted to Vegetated Coastal Wetlands									
Methane Emissions (MMT CO$_2$ Eq.)	0.25		0.24		0.20	0.19	0.18	0.17	0.16
Methane Emissions (kt CH$_4$)	9.88		9.74		7.97	7.60	7.22	6.85	6.48
Grassland Converted to Vegetated Coastal Wetlands									
Methane Emissions (MMT CO$_2$ Eq.)	+		+		+	+	+	+	+
Methane Emissions (kt CH$_4$)	0.01		0.01		0.05	0.05	0.06	0.07	0.07
Other Land Converted to Vegetated Coastal Wetlands									
Methane Emissions (MMT CO$_2$ Eq.)	+		+		0.01	0.01	0.01	0.01	0.01
Methane Emissions (kt CH$_4$)	0.08		0.14		0.33	0.37	0.40	0.43	0.47
Settlements Converted to Vegetated Coastal Wetlands									
Methane Emissions (MMT CO$_2$ Eq.)	+		+		+	+	+	+	+
Methane Emissions (kt CH$_4$)	0.01		+		+	+	+	+	+
Total Methane Emissions (MMT CO$_2$ Eq.)	**0.25**		**0.25**		**0.21**	**0.20**	**0.19**	**0.18**	**0.18**
Total Methane Emissions (kt CH$_4$)	**9.98**		**9.91**		**8.38**	**8.05**	**7.72**	**7.39**	**7.06**

Note: Totals may not sum due to independent rounding.

+ Absolute value does not exceed 0.005 MMT CO$_2$ Eq. or 0.005 kt CH$_4$.

Methodology

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil C stocks and CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands*.

Biomass Carbon Stock Changes

Biomass C stocks for *Land Converted to Vegetated Coastal Wetlands* are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating Vegetated Coastal Wetlands from ephemerally flooded upland Grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2019 from these datasets using the C-CAP change data closest in date to a given year. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[71]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014), and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass C stocks for Forest Land, Cropland, and Grassland that are lost with the conversion to *Vegetated Coastal Wetlands* were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass C stock values of each land use category (i.e., Forest Land, Cropland, and Grassland) from those of *Vegetated Coastal Wetlands* in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass C stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for *Lands Converted to Vegetated Coastal Wetlands* across all years. Tier 1 estimates of mangrove DOM C stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for Forest Land converted to Vegetated Coastal Wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to negligible for other land use conversions (i.e., other than Forest Land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2019 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the difference between Tier 1 DOM C stocks for Vegetated Coastal Wetlands and Forest Land. The difference between

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[71] See <https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public>; accessed October 2020

the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil C removals are estimated for *Land Converted to Vegetated Coastal Wetlands* across all years. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). To estimate soil C stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC Guidance, *Land Converted to Vegetated Coastal Wetlands* is assumed to remain in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Tier 2 level estimates of soil C stock changes associated with annual soil C accumulation from *Land Converted to Vegetated Coastal Wetlands* were developed using country-specific soil C removal factors multiplied by activity data of land area for *Land Converted to Vegetated Coastal Wetlands* for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil C accumulation to be instantaneously equivalent to that in natural settings and that soil C accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2019 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement*, and is applied to the area of *Land Converted to Vegetated Coastal Wetlands* on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement*. Because *Land Converted to Vegetated Coastal Wetlands* is held in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining to Vegetated Coastal Wetlands,* CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty and Time-Series Consistency

Underlying uncertainties in estimates of soil C removal factors, biomass change, DOM, and CH_4 emissions include error in uncertainties associated with Tier 2 literature values of soil C removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass C removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil C stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10-15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation

of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-80 for each carbon pool and the CH_4 emissions. The combined uncertainty is +/-42.5 percent. In 2019, the total flux was 0.16 MMT CO_2 Eq., with lower and upper estimates of 0.09 and 0.22 MMT CO_2 Eq.

Table 6-80: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes occurring within _Land Converted to Vegetated Coastal Wetlands_ (MMT CO₂ Eq. and Percent)

Source	2019 Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Estimate[a]			
		(MMT CO₂ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.1	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.02	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.2)	(0.2)	(0.1)	-17.8%	17.8%
Methane Emissions	0.2	0.12	0.23	-29.9%	29.9%
Total Uncertainty	**0.16**	**0.09**	**0.22**	**-42.2%**	**42.2%**

Note: Totals may not sum due to independent rounding.

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and Methodology sections.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads. Biomass C stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads prior to inclusion in the inventory and from IPCC reports. As a QC step, a check was undertaken confirming that Coastal Wetlands recognized by C-CAP represent a subset of Wetlands recognized by the NRI for marine coastal states. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil C stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the _Wetlands Supplement_.

Recalculations Discussion

As part of the addition of a 2016 C-CAP dataset, the previous datasets (1996, 2001, 2006, and 2011) were refined and reanalyzed using improved methods, software and techniques that were deemed important to incorporate in order to create the most accurate and representative product.

The addition of the 2016 C-CAP dataset resulted in changes in area calculations for 1990 to 1995 and 2011 through 2018, all years that previously used a change value that was the average change across all C-CAP time periods (1996 through 2011). For 1990 through 1995, the 1996 to 2000 C-CAP change data were used, and the 2011 to 2016 C-CAP change data were used for 2017 through 2019. This improvement results in fewer years where coastal wetland area is interpolated.

Although this change does not affect the area calculations presented here, a new organic soil geospatial layer was derived from CONUS distributions of histosols in the USDA's Soil Survey Geographic Database (SSURGO). The dataset is complete except for a large portion of the Florida Everglades that did not contain data. Incorporating this new dataset resulted in a large change in extents between organic and mineral soils, with far less area of organic soils nationally than previously recorded.

A corrigendum was published by Byrd et al. (2020) for non-forested aboveground biomass values initially presented in Byrd et al. (2018). The updated analyses resulted in increases in aboveground biomass carbon stocks across all wetland types and climate zones (except for the Puget Sound, which had a 0.1 t C ha^{-1} decrease); the average aboveground biomass increased from 1.93 to 3.02 t C ha^{-1}.

Belowground biomass carbon stocks are now included for coastal wetlands. They are based on Tier 2 root to shoot ratios from the *Wetlands Supplement* (IPCC 2014). This resulted in a 0.05 and 0.0001 MMT CO_2 Eq. (0.01 and 0.00003 MMT C) increase in 1990 and 2018, respectively, compared to the previous Inventory.[72]

Dead organic matter carbon fluxes are now included for estuarine forested wetlands and for Forest Land converted to Vegetated Coastal Wetlands. This update resulted in an increase in emissions of 0.09 and 0.02 MMT CO_2 Eq. (0.02 and 0.005 MMT C) in 1990 and 2018, respectively.

An update was made to how biomass C fluxes are calculated when lands are converted to Vegetated Coastal Wetlands. The loss of the converted land's former carbon stocks is now included, which applies to Forest Land, Grassland, and Cropland, and results in net emissions from biomass from coastal wetlands converted from Forest Land. The total loss and subsequent coastal wetland biomass gain is assumed to occur in the first year of conversion, although the loss and gain of C actually occurs over a longer period of time. This update, in addition to inclusion of belowground biomass and the corrigendum to aboveground biomass C stocks, resulted in an increase in emissions of 0.63 and 0.15 MMT CO_2 Eq. (0.17 and 0.04 MMT C) in 1990 and 2018, respectively.

Soil C accumulation and CH_4 emissions are now calculated as the cumulative flux from the area converted each year in addition to the prior 19 years. This results in greater soil C removals and CH_4 emissions across the entire reporting period. Soil C removals increased by 0.24 and 0.15 MMT CO_2 Eq. (0.06 and 0.04 MMT C) in 1990 and 2018, respectively. Methane emissions increased by 0.24 and 0.16 MMT CO_2 Eq. (9.4 and 6.5 kt CH_4) in 1990 and 2018, respectively.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stocks and biomass for coastal wetlands.[73] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent changes in soil C stocks and will be incorporated into the 2022 Inventory submission.

Currently, the only coastal wetland conversion that is reported in the Inventory is *Lands Converted to Vegetated Coastal Wetlands*. The next (2022) submission will include C stock change data for *Lands Converted to Unvegetated Open Water Coastal Wetlands*.

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[72] These values only include changes in the coastal wetland biomass stock emissions factors and do not include the updates of accounting for other land uses' biomass stock loss.

[73] See <https://serc.si.edu/coastalcarbon>; accessed October 2020.

6.10 Settlements Remaining Settlements (CRF Category 4E1)

Soil Carbon Stock Changes (CRF Category 4E1)

Soil organic C stock changes for *Settlements Remaining Settlements* occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in *Settlements Remaining Settlements*. This approach is consistent with the assumption of the Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in *Settlements Remaining Settlements*.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[74] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements Remaining Settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2015 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2018)[75] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The Inventory includes settlements on privately-owned lands in the conterminous United States and Hawaii. Alaska and the small amount of settlements on federal lands are not included in this Inventory even though these areas are part of the U.S. managed land base. This leads to a discrepancy with the total amount of managed area in *Settlements Remaining Settlements* (see Section 6 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future Inventory.

CO_2 emissions from drained organic soils in settlements are 15.9 MMT CO_2 Eq. (4.3 MMT C) in 2019 (See Table 6-81 and 6-82). Although the flux is relatively small, the amount has increased by over 41 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-81: Net CO$_2$ Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT CO$_2$ Eq.)

Soil Type	1990		2005		2015	2016	2017	2018	2019
Organic Soils	11.3		12.2		15.7	16.0	16.0	15.9	15.9

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[74] N$_2$O emissions from soils are included in the N$_2$O Emissions from Settlement Soils section.

[75] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Settlements Remaining Settlements* in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-82: Net CO₂ Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT C)

Soil Type	1990		2005		2015	2016	2017	2018	2019
Organic Soils	3.1		3.3		4.3	4.4	4.4	4.3	4.3

Methodology

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in *Settlements Remaining Settlements* (IPCC 2006). Organic soils in *Settlements Remaining Settlements* are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2018 NRI (USDA-NRCS 2018) with additional information from the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). It is assumed that all settlement area on organic soils is drained, and those areas are provided in Table 6-83 (See Section 6, Representation of the U.S. Land Base for more information). The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-83). The area of land on organic soils in *Settlements Remaining Settlements* has increased from 220 thousand hectares in 1990 to over 303 thousand hectares in 2015. The area of land on organic soils are not currently available from NRI for *Settlements Remaining Settlements* after 2015.

Table 6-83: Thousands of Hectares of Drained Organic Soils in *Settlements Remaining Settlements*

Year	Area (Thousand Hectares)
1990	220
2005	235
2014	291
2015	303
2016	ND
2017	ND
2018	ND
2019	ND

Note: No NRI data are available after 2015, designated as ND (No data)

To estimate CO₂ emissions from drained organic soils across the time series from 1990 to 2015, the total area of organic soils in *Settlements Remaining Settlements* is multiplied by the country-specific emission factors for *Cropland Remaining Cropland* under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

A linear extrapolation of the trend in the time series is applied to estimate the emissions from 2016 to 2019 because NRI activity data are not available for these years to determine the area of drained organic soils in *Settlements Remaining Settlements*. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2015, and in turn, the trend is used to approximate the 2016 to 2019 emissions. The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2015 as activity data become available.

Uncertainty and Time-Series Consistency

Uncertainty for the Tier 2 approach is derived using a Monte Carlo approach, along with additional uncertainty propagated through the Monte Carlo Analysis for 2016 to 2019 based on the linear time series model. The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 6-84. Soil C losses from drained organic soils in *Settlements Remaining Settlements* for 2019 are estimated to be between 7.5 and 24.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 53 percent below and 53 percent above the 2019 emission estimate of 15.9 MMT CO_2 Eq.

Table 6-84: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.9	7.5	24.3	-53%	53%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in the Introduction and Methodology sections.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

There were no recalculations to the 1990 through 2018 time series in this Inventory.

Planned Improvements

This source will be updated to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. See Table 6-85 for the amount of managed land area in *Settlements Remaining Settlements* that is not included in the Inventory due to these omissions. The managed settlements area that is not included in the Inventory is in the range of 150 to 160 thousand hectares each year. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-85: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

Year	Area (Thousand Hectares)		
	SRS Managed Land Area (Section 6)	SRS Area Included in Inventory	SRS Area Not Included in Inventory
1990	30,585	30,425	159
1991	30,589	30,430	159
1992	30,593	30,434	159
1993	30,505	30,346	159
1994	30,423	30,264	159

1995	30,365	30,206	159
1996	30,316	30,157	158
1997	30,264	30,105	158
1998	30,200	30,041	159
1999	30,144	29,992	152
2000	30,101	29,949	152
2001	30,041	29,889	152
2002	30,034	29,882	152
2003	30,530	30,378	152
2004	31,011	30,859	152
2005	31,522	31,370	152
2006	31,964	31,812	152
2007	32,469	32,317	152
2008	33,074	32,922	152
2009	33,646	33,494	152
2010	34,221	34,069	152
2011	34,814	34,662	152
2012	35,367	35,215	152
2013	36,308	36,156	152
2014	37,281	37,129	152
2015	38,210	38,058	152
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Changes in Carbon Stocks in Settlement Trees (CRF Source Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 115.9 MMT CO_2 Eq. (31.6 MMT C) over the period from 1990 through 2019. Net C sequestration from settlement trees in 2019 is estimated to be 129.8 MMT CO_2 Eq. (35.4 MMT C) (Table 6-86). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses vs tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base C flux estimates. Annual sequestration increased by 35 percent between 1990 and 2019 due to increases in settlement area and changes in tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas are less than in forests and this tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the C stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for *Forest Lands).*

Table 6-86: Net Flux from Trees in *Settlements Remaining Settlements* (MMT CO_2 Eq. and MMT C)[a]

Year	MMT CO_2 Eq.	MMT C
1990	(96.4)	(26.3)

2005	(117.4)	(32.0)
2014	(129.4)	(35.3)
2015	(130.4)	(35.6)
2016	(129.8)	(35.4)
2017	(129.8)	(35.4)
2018	(129.8)	(35.4)
2019	(129.8)	(35.4)

Note: Parentheses indicate net sequestration.
[a] These estimates include net CO_2 and C flux from
   trees on *Settlements Remaining Settlements* and
   Land Converted to Settlements as it is not possible
   to report on these separately at this time.

Methodology

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlements area is defined in Section 6 Representation of the U.S. Land Base as a land-use category representing developed areas. The data used to estimate settlement area within Section 6 comes from the NRI as updated through 2015 with the extension of the time series through 2018 based on assuming the settlements area is the same as 2015, while harmonizing these data with the FIA dataset, which are available through 2018, and the NLCD dataset, which is available through 2016. Settlement areas for 2019 are held constant with the 2018 values. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of CO_2 flux (Table 6-86) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. NLCD developed classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as Developed Open Space.

b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family

housing units." Plots designated as single family or low-density residential land were classified as Developed, Low Intensity.

c) "Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units." Plots designated as medium density residential, other urban or mixed urban were classified as Developed, Medium Intensity.

d) "Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover." Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as Developed, High Intensity.

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2011 and 2016 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2019: used 2011 NLCD tree cover adjusted with 2016 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net C sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate C in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross C sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration estimates to obtain estimates of net C sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[76] and Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-87). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service's i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total C stored and annual C sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-

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[76] See <http://www.itreetools.org>.

weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to C by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. Estimated C storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-87: Carbon Storage (kg C/m^2 tree cover), Gross and Net Sequestration (kg C/m^2 tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

City	Storage	SE	Sequestration Gross	SE	Net	SE	Ratio[a]	Tree Cover	SE
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7
Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7

San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4
South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE – Standard Error
NA – Not Available
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration – that is, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each tree were then scaled up to city estimates using tree population information. Total C sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross C sequestration accounts for all C sequestered, net C sequestration for settlement trees considers C emissions associated with tree death and removals. The third step in the methodology estimates net C emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross C emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-88) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's

annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual C sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-88). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual C sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Net state annual C sequestration (t C/yr) = Gross state sequestration rate (t C/ha/yr) × Net to Gross state sequestration ratio × state settlement Area (ha) × % state tree cover in settlement area

The results for all 50 states and the District of Columbia are given in Table 6-88. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net C sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-88: Estimated Annual C Sequestration (Metric Tons C/Year), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m²/ year) for settlement areas in United States by State and the District of Columbia (2019)

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	2,060,001	1,501,070	53.5	0.376	0.274	0.73
Alaska	111,722	81,409	47.4	0.169	0.123	0.73
Arizona	172,750	125,878	4.6	0.388	0.283	0.73
Arkansas	1,266,164	922,622	48.9	0.362	0.264	0.73
California	2,007,869	1,463,083	16.9	0.426	0.311	0.73
Colorado	142,719	103,996	8.0	0.216	0.157	0.73
Connecticut	618,683	450,818	58.7	0.262	0.191	0.73
Delaware	97,533	71,070	24.4	0.366	0.267	0.73
DC	11,995	8,741	25.1	0.366	0.267	0.73
Florida	4,322,610	3,149,776	40.3	0.520	0.379	0.73
Georgia	3,411,478	2,485,857	56.3	0.387	0.282	0.73
Hawaii	285,700	208,182	41.7	0.637	0.464	0.73
Idaho	59,611	43,437	7.4	0.201	0.146	0.73
Illinois	662,891	483,032	15.5	0.310	0.226	0.73
Indiana	472,905	437,275	17.1	0.274	0.254	0.92
Iowa	177,692	129,480	8.6	0.263	0.191	0.73
Kansas	290,461	226,027	10.8	0.310	0.241	0.78
Kentucky	926,269	674,949	36.8	0.313	0.228	0.73
Louisiana	1,512,145	1,101,861	47.0	0.435	0.317	0.73
Maine	394,471	287,441	55.5	0.242	0.176	0.73
Maryland	818,044	596,088	40.1	0.353	0.257	0.73
Massachusetts	1,002,723	730,659	57.2	0.278	0.203	0.73
Michigan	1,343,325	978,847	34.7	0.241	0.175	0.73
Minnesota	313,364	228,340	13.1	0.251	0.183	0.73
Mississippi	1,518,448	1,106,454	57.3	0.377	0.275	0.73
Missouri	850,492	619,732	23.2	0.313	0.228	0.73
Montana	48,911	35,640	4.9	0.201	0.147	0.73

Nebraska	98,584	83,192	7.3	0.261	0.220	0.84
Nevada	41,181	30,008	4.8	0.226	0.165	0.73
New Hampshire	363,989	265,229	59.3	0.238	0.174	0.73
New Jersey	904,868	659,355	40.7	0.321	0.234	0.73
New Mexico	177,561	129,384	10.2	0.288	0.210	0.73
New York	1,531,415	1,115,903	39.9	0.263	0.192	0.73
North Carolina	3,064,797	2,233,239	54.1	0.341	0.249	0.73
North Dakota	18,492	8,787	1.8	0.244	0.116	0.48
Ohio	1,248,841	909,999	28.2	0.271	0.198	0.73
Oklahoma	699,044	509,376	22.1	0.364	0.265	0.73
Oregon	682,468	497,297	39.9	0.265	0.193	0.73
Pennsylvania	1,794,939	1,307,927	40.2	0.267	0.195	0.73
Rhode Island	121,940	88,855	50.0	0.283	0.206	0.73
South Carolina	1,801,029	1,312,364	53.8	0.370	0.269	0.73
South Dakota	29,489	25,573	2.9	0.258	0.224	0.87
Tennessee	1,591,278	1,422,789	41.1	0.332	0.297	0.89
Texas	4,239,494	3,089,211	28.5	0.403	0.294	0.73
Utah	118,880	86,625	11.7	0.235	0.172	0.73
Vermont	176,564	128,658	50.6	0.234	0.170	0.73
Virginia	1,968,537	1,434,422	52.9	0.321	0.234	0.73
Washington	1,063,871	775,216	37.6	0.282	0.206	0.73
West Virginia	699,320	509,577	64.1	0.264	0.192	0.73
Wisconsin	697,863	508,515	25.9	0.246	0.180	0.73
Wyoming	29,984	21,849	4.7	0.199	0.145	0.73
Total	**48,065,406**	**35,405,113**				

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net C sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-89). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there is likely some overlap between the settlement tree C estimates and the forest tree C estimates (e.g., Nowak et al. 2013). Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2019. The results of this quantitative uncertainty analysis are summarized in Table 6-89. The change in C stocks in *Settlement Trees* in 2019 was estimated to be between -195.4 and -62.2 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2019 flux estimate of -129.8 MMT CO_2 Eq.

Table 6-89: Approach 2 Quantitative Uncertainty Estimates for Net CO₂ Flux from Changes in C Stocks in Settlement Trees (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Flux Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Flux Estimate			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO₂	(129.8)	(195.42)	(62.22)	-51%	52%

Note: Parentheses indicate negative values or net sequestration.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

There were no recalculations to the 1990 through 2018 time series in this Inventory.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6 Representation of the U.S. Land Base, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between *Settlement Trees* and the forest land categories. Estimates for *Settlement Trees* are based on tree cover in settlement areas. What needs to be determined is how much of this settlement area tree cover might also be accounted for in "forest" area assessments as some of these forests may fall within settlement areas. For example, "forest" as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the C reported in the Forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown. Future research may also enable more complete coverage of changes in the C stock of trees for all settlements land.

To provide more accurate emissions estimates in the future, the following actions will be taken:

a) Photo-interpret settlement tree cover in 2021 to update tree cover estimates and trends
b) Update photo-interpretation for settlement areas using 2016 NLCD developed land information
c) Develop spatially explicit and spatially continuous representations of land to eliminate the overlap between forest and settlement areas, as well as allow for improved estimates in "settlement areas"

N₂O Emissions from Settlement Soils (CRF Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N₂O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer

application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *Histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., ammonia [NH_3] and nitrogen oxide [NO_x] volatilization, nitrate [NO_3^-] leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in *Settlements Remaining Settlements*[77] are 2.4 MMT CO_2 Eq. (8 kt of N_2O) in 2019. There is an overall increase of 20 percent from 1990 to 2019 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-90.

Table 6-90: N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2015	2016	2017	2018	2019
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.6**	**2.5**	**1.8**	**1.9**	**2.0**	**2.0**	**2.0**
Synthetic Fertilizers	0.8	1.6	0.8	0.9	1.0	1.0	1.1
Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.6	0.7	0.8	0.8	0.8	0.8	0.8
Indirect N_2O Emissions from Soils	**0.4**	**0.6**	**0.3**	**0.3**	**0.4**	**0.4**	**0.4**
Total	**2.0**	**3.1**	**2.2**	**2.2**	**2.3**	**2.4**	**2.4**
kt N_2O							
Direct N_2O Emissions from Soils	**6**	**9**	**6**	**6**	**7**	**7**	**7**
Synthetic Fertilizers	3	6	3	3	3	4	4
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	2	2	3	3	3	3	3
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**7**	**11**	**7**	**8**	**8**	**8**	**8**

Methodology

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.2—Wastewater Treatment for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2019 are based on 2012 values adjusted for annual total N fertilizer sales in the United States because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. The total amount of fertilizer N

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[77] Estimates of Soil N_2O for *Settlements Remaining Settlements* include emissions from *Land Converted to Settlements* because it was not possible to separate the activity data.

applied to settlements is multiplied by the IPCC default emission factor (1 percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2012.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2019.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2015 NRI (USDA-NRCS 2018) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). To estimate annual emissions from 1990 to 2015, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). This Inventory does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future Inventory.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2015 for fertilizer and from 1990 to 2019 for biosolids.

A linear extrapolation of the trend in the time series is applied to estimate the direct and indirect N_2O emissions for fertilizer and drainage of organic soils from 2016 to 2019 because N fertilizer inputs and area data for these two sources have not been compiled for the latter part of the time series. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2015, and in turn, the trend is used to approximate the 2016 to 2019 emissions. The time series will be recalculated for the years beyond 2015 in a future inventory with the methods described above for 1990 to 2015. This Inventory does incorporate updated activity data on biosolids application in settlements through 2019.

Uncertainty and Time-Series Consistency

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variation in the total amount of fertilizer N and biosolids application, which in turn, leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[78] Uncertainty in the area of drained organic soils is based on the estimated variance from the NRI survey (USDA-NRCS 2018). For 2016 to 2019, there is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods.

For biosolids, there is uncertainty in the amounts of biosolids applied to non-agricultural lands and used in surface disposal. These uncertainties are derived from variability in several factors, including: (1) N content of biosolids; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the biosolids disposal practice

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[78] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

distributions to non-agricultural land application and surface disposal. In addition, there is uncertainty in the direct and indirect emission factors that are provided by IPCC (2006).

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-91. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2019 are estimated to be between 1.4 and 2.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 29 percent below to 41 percent above the 2019 emission estimate of 2.0 MMT CO_2 Eq. Indirect N_2O emissions in 2019 are between 0.2 and 0.5 MMT CO_2 Eq., ranging from 39 percent below to 39 percent above the estimate of 0.4 MMT CO_2 Eq.

Table 6-91: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
Settlements Remaining Settlements			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct N_2O Emissions from Soils	N_2O	2.0	1.4	2.9	-29%	41%
Indirect N_2O Emissions from Soils	N_2O	0.4	0.2	0.5	-39%	39%

Note: These estimates include direct and indirect N_2O emissions from *Settlements Remaining Settlements* and *Land Converted to Settlements* because it was not possible to separate the activity data.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in the Introduction and Methodology sections.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked. An error was found in the uncertainty calculation that was corrected.

Recalculations Discussion

There were no recalculations to the 1990 through 2018 time series in this Inventory.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amount and area of drained organic soils will be compiled to update emissions estimates from 2016 to 2019 in a future Inventory.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRF Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the Inventory are associated with particular land uses. For example, harvested wood products are reported under *Forest Land Remaining Forest Land* because these wood products originated from the forest ecosystem. Similarly, C stock changes in yard trimmings and food scraps are reported under *Settlements Remaining Settlements* because the bulk of the C, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this Inventory they are reported with the yard trimmings in the *Settlements Remaining Settlements* section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1 Representation of the U.S. Land Base), and reporting these C stock changes that occur entirely within landfills fits most appropriately within the *Settlements Remaining Settlements* section.

Both the estimated amount of yard trimmings collected annually and the fraction that is landfilled have been declining. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2019). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent estimated 0.5 percent decrease between 1990 and 2019 in the tonnage of yard trimmings generated (i.e., collected for composting or disposal in landfills). At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills—from 72 percent in 1990 to 25 percent in 2019. The net effect of the reduction in generation and the increase in composting is a 66 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by an estimated 70 percent since 1990, and while the proportion of total food scraps generated that are eventually discarded in landfills has decreased slightly, from an estimated 82 percent in 1990 to 75 percent in 2019, the tonnage disposed of in landfills has increased considerably (by an estimated 57 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2019, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual carbon stock *net changes* from food scraps have generally decreased as well (as shown in Table 6-92 and Table 6-93). As described in the Methodology section, the carbon stocks are modeled using data on the amount of food scraps landfilled since 1960. These food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable 'older' carbon stock, thus resulting in less annual change in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual *net change* landfill C storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 10.2 MMT CO_2 Eq. (2.8 MMT C) in 2019 (Table 6-92 and Table 6-93).

Table 6-92: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO₂ Eq.)

Carbon Pool	1990	2005	2015	2016	2017	2018	2019
Yard Trimmings	**(20.1)**	**(7.5)**	**(7.2)**	**(6.3)**	**(6.3)**	**(6.4)**	**(6.4)**
Grass	(1.7)	(0.6)	(0.6)	(0.5)	(0.5)	(0.6)	(0.6)
Leaves	(8.7)	(3.4)	(3.4)	(3.0)	(3.0)	(3.0)	(3.0)
Branches	(9.8)	(3.4)	(3.2)	(2.8)	(2.8)	(2.8)	(2.8)
Food Scraps	**(4.4)**	**(3.9)**	**(3.9)**	**(3.7)**	**(3.5)**	**(3.4)**	**(3.8)**
Total Net Flux	**(24.5)**	**(11.4)**	**(11.1)**	**(10.0)**	**(9.8)**	**(9.8)**	**(10.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-93: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2015	2016	2017	2018	2019

Yard Trimmings	**(5.5)**	**(2.0)**	**(2.0)**	**(1.7)**	**(1.7)**	**(1.7)**	**(1.7)**
Grass	(0.5)	(0.2)	(0.2)	(0.1)	(0.1)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(0.9)	(0.8)	(0.8)	(0.8)	(0.8)
Branches	(2.7)	(0.9)	(0.9)	(0.8)	(0.8)	(0.8)	(0.8)
Food Scraps	**(1.2)**	**(1.1)**	**(1.1)**	**(1.0)**	**(1.0)**	**(0.9)**	**(1.0)**
Total Net Flux	**(6.7)**	**(3.1)**	**(3.0)**	**(2.7)**	**(2.7)**	**(2.7)**	**(2.8)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years and are based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled C stocks for a given year, the following data and factors were assembled: (1) The composition of the yard trimmings; (2) the mass of yard trimmings and food scraps discarded in landfills; (3) the C storage factor of the landfilled yard trimmings and food scraps; and (4) the rate of decomposition of the degradable C. The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2017* (EPA 2019), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2016, and 2017. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, and 2015 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2018 and 2019 were unavailable, landfilled material generation, recovery, and disposal data for 2018 and 2019 were set equal to 2017 values.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-94).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid

sample can be expressed as a proportion of the initial C (shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-94).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are reported in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-94.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

Similar to the methodology in the Landfills section of the Inventory (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates.

To maintain consistency between landfill methodologies across the Inventory, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. The component-specific decay rates are shown in Table 6-94.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to Equation 1:

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t	=	Year for which C stocks are being estimated (year),
i	=	Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$	=	Stock of C in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$	=	Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),

n	=	Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i	=	Moisture content of waste i (percent of water),
CS_i	=	Proportion of initial C that is stored for waste i (percent),
ICC_i	=	Initial C content of waste i (percent),
e	=	Natural logarithm, and
k	=	First-order decay rate for waste i, (year^{-1}).

For a given year t, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year t is calculated in as the change in C stock compared to the preceding year according to Equation 2:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 1, the C placed in a landfill in year n is tracked for each year t through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2019, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2019), the total landfill C from food scraps in 2019 was 47.3 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2019, yielding a value of 280.1 million metric tons (as shown in Table 6-95). In the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-93) is the difference in the landfill C stock for the following year (2020 C stock was forecast using 1990 to 2019 C stocks) and the stock in the current year. For example, the net change in 2019 shown in Table 6-93 (2.8 MMT C) is equal to the stock in 2020 (282.9 MMT C) minus the stock in 2019 (280.1 MMT C). The C stocks calculated through this procedure are shown in Table 6-95.

Table 6-94: Moisture Contents, C Storage Factors (Proportions of Initial C Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year^{-1})	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-95: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2015	2016	2017	2018	2019	2020
Yard Trimmings	156.0	203.1	225.7	227.7	229.4	261.1	232.8	234.6
Branches	14.6	18.1	20.2	20.3	20.5	20.6	20.8	20.9
Leaves	66.7	87.4	97.7	98.6	99.4	100.2	101.0	101.9
Grass	74.7	97.7	107.8	108.7	109.5	110.2	111.0	111.8
Food Scraps	17.9	33.2	43.3	44.4	45.4	46.3	47.3	48.3
Total Carbon Stocks	173.9	236.3	269.0	272.0	274.8	277.4	280.1	282.9

Note: Totals may not sum due to independent rounding.
[a] 2020 C stock estimate was forecasted using 1990 to 2019 data.

To develop the 2020 C stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2020, based on data from 1990 through 2019. These forecasted values were used to calculate net changes in carbon stocks for 2019. Excel's FORECAST.ETS function was used to predict a 2020 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2020.

Uncertainty and Time-Series Consistency

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2019. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-96. Total yard trimmings and food scraps CO_2 flux in 2019 was estimated to be between -16.3 and -4.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 61 percent below to 57 percent above the 2019 flux estimate of -10.2 MMT CO_2 Eq.

Table 6-96: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(10.2)	(16.3)	(4.4)	-61%	57%

Note: Parentheses indicate negative values or net C sequestration.
[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for *Landfilled Yard Trimmings and Food Scraps* included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The current Inventory has been revised to reflect updated data from the most recent *Advancing Sustainable Materials Management: Facts and Figures* report. Recalculations based on these updates resulted in 2.1 percent change in the annual carbon stocks and sequestration values as compared to the previous inventory values. The

largest changes occurred in the most recent years: a 7.7 percent increase in sequestration in 2015, a 16.3 percent increase in sequestration in 2016, an 18.4 percent increase in sequestration in 2017, and a 19.0 percent increase in sequestration in 2018. Large changes can be attributed to updates to 2015, 2016, and 2017 yard trimmings and food scraps landfilled values reported in *Advancing Sustainable Materials Management: Facts and Figures 2017* (EPA 2019). A large increase in sequestration in 2018 can be attributed to updated generation values as well - 2018 landfill data were unavailable and were reported as 2017 values. An increase of less than 0.1 percent occurred in 2014 due to a small increase in calculated leaf C mass and grass C mass values for 2015 between the current and previous Inventory.

Planned Improvements

Future work is planned to evaluate the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the Waste chapter. For example, the Waste chapter does not distinguish landfill CH_4 emissions from yard trimmings and food scraps separately from landfill CH_4 emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps. In future years, as time and resources allow, EPA will further evaluate both categories to ensure consistency.

In addition, data from recent peer-reviewed literature will be evaluated that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values.

EPA will also investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches. Currently the inventory calculations use 2010 U.S. Census data. EPA will evaluate using decay rates that vary over time based on Census data changes over time.

Yard waste composition will also be investigated to determine if changes need to be made based on changes in residential practices, a review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with Inventory estimates.

Finally, EPA will review available data to ensure all types of landfilled yard trimmings and food scraps are being included in Inventory estimates, such as debris from road construction and commercial food waste not included in other chapter estimates.

6.11   Land Converted to Settlements (CRF Category 4E2)

Land Converted to Settlements includes all settlements in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[79] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils on settlements in federal lands are also not included in this Inventory. Consequently, there is a discrepancy between the total

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[79] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Settlements* in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

amount of managed area for *Land Converted to Settlements* (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis.

Land use change can lead to large losses of carbon (C) to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for *Land Converted to Settlements,* but there is limited reporting of other pools in this Inventory. Loss of aboveground and belowground biomass, dead wood and litter C are reported for *Forest Land Converted to Settlements*, but not for other land use conversions to settlements.

Forest Land Converted to Settlements is the largest source of emissions from 1990 to 2019, accounting for approximately 76 percent of the average total loss of C among all of the land use conversions in *Land Converted to Settlements.* Losses of aboveground and belowground biomass, dead wood and litter C losses in 2019 are 36.9, 7.2, 6.7, and 9.9 MMT CO_2 Eq., respectively (10.1, 2.0, 1.8, and 2.7 MMT C). Mineral and organic soils also lost 16.2 and 2.4 MMT CO_2 Eq. in 2019 (4.4 and 0.6 MMT C). The total net flux is 79.2 MMT CO_2 Eq. in 2019 (21.6 MMT C), which is a 26 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Tables 6-97 and 6-98). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter C.

Table 6-97: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Settlements* (MMT CO_2 Eq.)

	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to Settlements	**3.4**	**9.8**	**6.2**	**6.0**	**6.0**	**5.9**	**5.9**
Mineral Soils	2.8	8.4	5.3	5.2	5.2	5.2	5.1
Organic Soils	0.6	1.3	0.8	0.8	0.8	0.8	0.8
Forest Land Converted to Settlements	**54.6**	**59.9**	**63.0**	**62.9**	**62.9**	**62.9**	**62.9**
Aboveground Live Biomass	32.5	35.1	36.9	36.9	36.9	36.9	36.9
Belowground Live Biomass	6.3	6.8	7.2	7.2	7.2	7.2	7.2
Dead Wood	5.8	6.3	6.7	6.7	6.7	6.7	6.7
Litter	8.7	9.4	9.9	9.9	9.9	9.9	9.9
Mineral Soils	1.1	2.0	2.0	1.9	1.9	1.9	1.9
Organic Soils	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Grassland Converted to Settlements	**5.2**	**16.3**	**11.9**	**11.3**	**11.3**	**11.3**	**11.3**
Mineral Soils	4.6	14.9	11.0	10.4	10.4	10.4	10.4
Organic Soils	0.6	1.4	0.9	0.9	0.9	0.9	0.9
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**
Mineral Soils	(0.4)	(1.6)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Organic Soils	+	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Converted to Settlements	**+**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mineral Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	+	0.4	0.3	0.3	0.3	0.3	0.3
Total Aboveground Biomass Flux	**32.5**	**35.1**	**36.9**	**36.9**	**36.9**	**36.9**	**36.9**
Total Belowground Biomass Flux	**6.3**	**6.8**	**7.2**	**7.2**	**7.2**	**7.2**	**7.2**
Total Dead Wood Flux	**5.8**	**6.3**	**6.7**	**6.7**	**6.7**	**6.7**	**6.7**
Total Litter Flux	**8.7**	**9.4**	**9.9**	**9.9**	**9.9**	**9.9**	**9.9**
Total Mineral Soil Flux	**8.1**	**23.8**	**17.0**	**16.3**	**16.2**	**16.2**	**16.2**
Total Organic Soil Flux	**1.4**	**3.6**	**2.5**	**2.4**	**2.4**	**2.4**	**2.4**
Total Net Flux	**62.9**	**85.0**	**80.1**	**79.4**	**79.3**	**79.3**	**79.2**

Note: Parentheses indicate negative values or net C sequestration.

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq.

Table 6-98: Net CO$_2$ Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Settlements* **(MMT C)**

	1990	2005	2015	2016	2017	2018	2019
Cropland Converted to							
Settlements	**0.9**	**2.7**	**1.7**	**1.6**	**1.6**	**1.6**	**1.6**
Mineral Soils	0.8	2.3	1.5	1.4	1.4	1.4	1.4
Organic Soils	0.2	0.4	0.2	0.2	0.2	0.2	0.2
Forest Land Converted to							
Settlements	**14.9**	**16.3**	**17.2**	**17.1**	**17.1**	**17.1**	**17.1**
Aboveground Live Biomass	8.9	9.6	10.1	10.1	10.1	10.1	10.1
Belowground Live Biomass	1.7	1.9	2.0	2.0	2.0	2.0	2.0
Dead Wood	1.6	1.7	1.8	1.8	1.8	1.8	1.8
Litter	2.4	2.6	2.7	2.7	2.7	2.7	2.7
Mineral Soils	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to							
Settlements	**1.4**	**4.4**	**3.2**	**3.1**	**3.1**	**3.1**	**3.1**
Mineral Soils	1.3	4.1	3.0	2.8	2.8	2.8	2.8
Organic Soils	0.2	0.4	0.3	0.2	0.2	0.2	0.2
Other Lands Converted to							
Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.1)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.3)
Organic Soils	+	+	+	+	+	+	0.0
Wetlands Converted to							
Settlements	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	+	+	+	+	+	0.0
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Aboveground Biomass Flux	**8.9**	**9.6**	**10.1**	**10.1**	**10.1**	**10.1**	**10.1**
Total Belowground Biomass Flux	**1.7**	**1.9**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Total Dead Wood Flux	**1.6**	**1.7**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Litter Flux	**2.4**	**2.6**	**2.7**	**2.7**	**2.7**	**2.7**	**2.7**
Total Mineral Soil Flux	**2.2**	**6.5**	**4.6**	**4.4**	**4.4**	**4.4**	**4.4**
Total Organic Soil Flux	**0.4**	**1.0**	**0.7**	**0.7**	**0.7**	**0.6**	**0.6**
Total Net Flux	**17.1**	**23.2**	**21.9**	**21.6**	**21.6**	**21.6**	**21.6**

Note: Parentheses indicate negative values or net C sequestration.

+ Absolute value does not exceed 0.05 MMT C.

Methodology

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Settlements*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to settlements, as well as (2) the impact from all land use conversions to settlements on soil organic C stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for *Forest Land Converted to Settlements.* Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020), however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks on these converted lands were assumed to be zero. The difference between the stocks is reported as the stock

change under the assumption that the change occurred in the year of the conversion. If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory, which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for *Land Converted to Settlements* according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018).

NRI survey locations are classified as *Land Converted to Settlements* in a given year between 1990 and 2015 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Settlements* in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate C stock changes for *Land Converted to Settlements* on mineral soils from 1990 to 2015. Data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific C stock change factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2015 NRI survey data (USDA-NRCS 2018) do not provide the information needed to assign different land use subcategories to settlements, such as turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic C with conversion to settlements under the assumption that there are additional soil organic C losses with land clearing, excavation and other activities associated with

development. More specific factor values can be derived in future inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

A linear extrapolation of the trend in the time series is applied to estimate soil organic C stock changes from 2016 to 2019 because NRI activity data are not available for these years. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in stock changes over time from 1990 to 2015, and in turn, the trend is used to approximate stock changes from 2016 to 2019. The Tier 2 method described previously will be applied to recalculate the 2016 to 2019 emissions in a future Inventory.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Settlements* are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing C at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2 emissions from 1990 to 2015, the area of organic soils in *Land Converted to Settlements* is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (See Annex 3.12 for more information). Similar to the mineral soil organic C stocks changes, a linear extrapolation of the trend in the time series is applied to estimate the emissions from 2016 to 2019 because NRI activity data are not available for these years to determine the area of *Land Converted to Settlements*.

Uncertainty and Time-Series Consistency

The uncertainty analysis for C losses with *Forest Land Converted to Settlements* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13. The uncertainty analysis for mineral soil organic C stock changes and annual C emission estimates from drained organic soils in *Land Converted to Settlements* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-99 for each subsource (i.e., biomass C, dead wood, litter, soil organic C in mineral soil and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., as described in the previous paragraph. There are also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic C stock changes from 2016 to 2019. The combined uncertainty for total C stocks in *Land Converted to Settlements* ranges from 33 percent below to 34 percent above the 2019 stock change estimate of 79.2 MMT CO_2 Eq.

Table 6-99: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Settlements* (MMT CO_2 Eq. and Percent)

Source	2019 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**5.9**	**2.3**	**9.5**	-61%	61%
Mineral Soil C Stocks	5.1	1.6	8.7	-69%	69%
Organic Soil C Stocks	0.8	0.1	1.4	-82%	82%
Forest Land Converted to Settlements	**62.9**	**38.5**	**87.4**	-39%	39%
Aboveground Biomass C Stocks	36.9	14.0	59.9	-62%	62%
Belowground Biomass C Stocks	7.2	2.7	11.7	-62%	62%
Dead Wood	6.7	3.5	10.9	-47%	62%

Litter	9.9	3.7	16.0	-62%	62%
Mineral Soil C Stocks	1.9	1.4	2.4	-27%	28%
Organic Soil C Stocks	0.3	0.1	0.5	-68%	69%
Grassland Converted to Settlements	**11.3**	**6.6**	**15.9**	**-41%**	**41%**
Mineral Soil C Stocks	10.4	5.8	15.0	-44%	44%
Organic Soil C Stocks	0.9	0.1	1.6	-85%	85%
Other Lands Converted to Settlements	**(1.2)**	**(1.9)**	**(0.4)**	**-62%**	**62%**
Mineral Soil C Stocks	(1.3)	(2.0)	(0.6)	-55%	55%
Organic Soil C Stocks	0.1	(0.1)	0.3	-160%	160%
Wetlands Converted to Settlements	**0.4**	**0.1**	**0.9**	**-142%**	**142%**
Mineral Soil C Stocks	0.1	+	0.1	-96%	96%
Organic Soil C Stocks	0.3	(0.2)	0.8	-172%	172%
Total: Land Converted to Settlements	**79.2**	**52.8**	**105.9**	**-33%**	**34%**
Aboveground Biomass C Stocks	**36.9**	**14.0**	**59.9**	**-62%**	**62%**
Belowground Biomass C Stocks	**7.2**	**2.7**	**11.7**	**-62%**	**62%**
Dead Wood	**6.7**	**3.5**	**10.9**	**-47%**	**62%**
Litter	**9.9**	**3.7**	**16.0**	**-62%**	**62%**
Mineral Soil C Stocks	**16.2**	**10.3**	**22.0**	**-36%**	**36%**
Organic Soil C Stocks	**2.4**	**(6.1)**	**10.8**	**-356%**	**356%**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

There were no recalculations in this Inventory.

Planned Improvements

A planned improvement for the *Land Converted to Settlements* category is to develop an inventory of mineral soil organic C stock changes in Alaska and losses of C from drained organic soils in federal lands. This includes C stock changes for biomass, dead organic matter and soils. See Table 6-100 for the amount of managed land area in *Land Converted to Settlements* that is not included in the Inventory due to these omissions. The managed area that is not included in the Inventory ranges between 0 and about 600 thousand hectares depending on the year.

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the Inventory to included C losses associated with drained organic soils in settlements occurring on federal lands

New land representation data will also be compiled, and the time series recalculated for the latter years in the time series that are estimated using data splicing methods in this Inventory. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-100: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

Year	Area (Thousand Hectares)		
	LCS Managed Land Area (Section 6.1)	LCS Area Included in Inventory	LCS Area Not Included in Inventory
1990	2,861	2,861	0
1991	3,238	3,238	0
1992	3,592	3,592	0
1993	4,178	4,107	72
1994	4,777	4,630	147
1995	5,384	5,161	223
1996	5,927	5,658	269
1997	6,520	6,174	346
1998	7,065	6,650	416
1999	7,577	7,116	461
2000	8,095	7,568	528
2001	8,544	7,947	597
2002	8,886	8,284	602
2003	8,941	8,335	606
2004	8,957	8,345	612
2005	8,947	8,341	606
2006	8,959	8,352	607
2007	8,902	8,295	607
2008	8,722	8,111	610
2009	8,541	7,930	611
2010	8,335	7,725	611
2011	8,108	7,498	611
2012	7,918	7,298	620
2013	7,504	6,932	572
2014	7,087	6,586	501
2015	6,589	6,165	424
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.12 Other Land Remaining Other Land (CRF Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of *Other Land Remaining Other Land* is known (see Table 6-5), research is ongoing to track C pools in this land use. Until such time that reliable and comprehensive estimates of C for *Other Land Remaining Other Land* can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on *Other Land Remaining Other Land* at this time.

6.13 Land Converted to Other Land (CRF Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-5), research is ongoing to track C across Other Land Remaining Other Land and Land Converted to Other Land. Until such time that reliable and comprehensive estimates of C across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on Land Converted to Other Land from fluxes on Other Land Remaining Other Land at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills accounted for approximately 17.4 percent of total U.S. anthropogenic methane (CH_4) emissions in 2019, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and discharge, composting of organic waste, and stand-alone anaerobic digestion accounted for approximately 2.8 percent, 0.3 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. Nitrous oxide emissions from composting were also estimated. Together, these waste activities account for 6.2 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2.

Figure 7-1: 2019 Waste Chapter Greenhouse Gas Sources
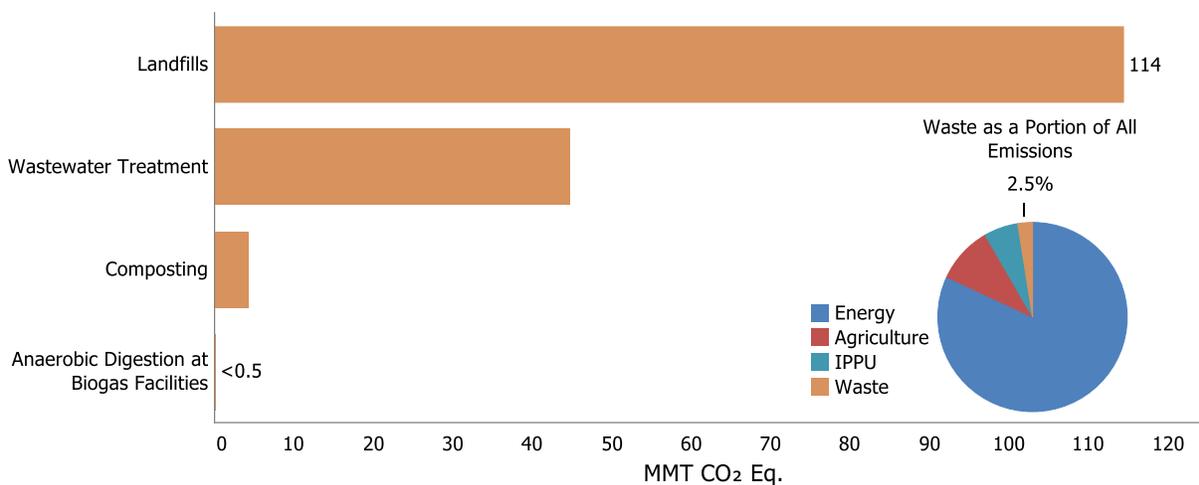
Figure 7-2: Trends in Waste Chapter Greenhouse Gas Sources
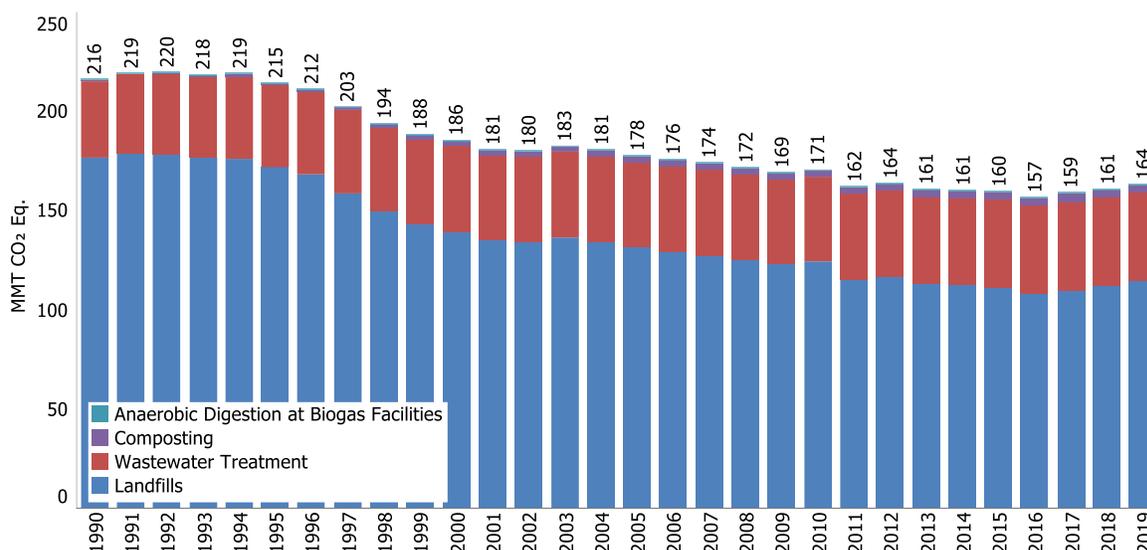
Overall, in 2019, waste activities generated emissions of 163.7 MMT CO_2 Eq., or 2.5 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CH_4	**197.1**	**153.4**	**132.5**	**129.2**	**130.5**	**132.9**	**135.3**
Landfills	176.6	131.4	111.4	108.0	109.4	112.1	114.5
Wastewater Treatment	20.2	20.1	18.8	18.7	18.5	18.4	18.4
Composting	0.4	1.9	2.1	2.3	2.4	2.3	2.3
Anaerobic Digestion at Biogas Facilities	+	0.1	0.2	0.2	0.2	0.2	0.2
N_2O	**19.0**	**24.6**	**27.3**	**27.9**	**28.6**	**28.2**	**28.4**
Wastewater Treatment	18.7	23.0	25.4	25.9	26.4	26.1	26.4
Composting	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Total	**216.2**	**178.0**	**159.8**	**157.1**	**159.0**	**161.1**	**163.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
CH_4	**7,885**	**6,135**	**5,301**	**5,166**	**5,218**	**5,317**	**5,414**
Landfills	7,063	5,255	4,456	4,321	4,375	4,482	4,580
Wastewater Treatment	806	803	753	747	739	737	736
Composting	15	75	85	91	98	90	91
Anaerobic Digestion at Biogas Facilities	1	2	7	7	7	7	7
N_2O	**64**	**83**	**91**	**94**	**96**	**94**	**95**
Wastewater Treatment	63	77	85	87	89	88	88
Composting	1	6	6	7	7	7	7

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO$_2$), CH$_4$, and N$_2$O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2019 resulted in 11.8 MMT CO$_2$ Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2018) to ensure that the trend is accurate. Based on the availability of updated methodological guidance from *2019 Refinement* (IPCC 2019), EPA revised the methodologies used to estimate CH$_4$ and N$_2$O emissions from domestic wastewater treatment as well as the methodology used to estimate CH$_4$ emissions from industrial wastewater treatment. EPA also added N$_2$O emission estimates from industrial wastewater treatment using a methodology based on the *2019 Refinement* (IPCC 2019). EPA also added emissions estimates from stand-alone anaerobic digestion to the Waste Chapter. For more information on specific methodological updates, please see the Recalculations for each category, in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater or the amount of CH$_4$ flared at composting sites. Emissions reported in the Waste chapter for landfills, wastewater treatment, and stand-alone anaerobic digestion include those from all 50 states, including Hawaii and Alaska, as well as from the District of Columbia. Emissions from wastewater treatment include most U.S. Territories except for Pacific Islands. Those emission are likely insignificant as those Pacific Islands have no permanent population . Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small. Similarly, we are not aware of any anerobic digestion at biogas facilities in U.S. territories, but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this inventory.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO$_2$ underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories.

Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from Municipal Solid Waste (MSW) landfills (see section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2019 of the Inventory. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRF Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current Inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations or CFR in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);
- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. However, the *2006 IPCC Guidelines* set an international convention to not report biogenic CO_2 from activities in the Waste sector (IPCC 2006). Net carbon dioxide flux from carbon stock changes in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Additionally, emissions of NMOC and VOC are not estimated because they are emitted in trace amounts. Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas – that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 60 years or longer as the degradable waste decomposes over time.

In 2019, landfill CH_4 emissions were approximately 114.5 MMT CO_2 Eq. (4,580 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 87 percent of total landfill emissions (99.4 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (15.1 MMT CO_2 Eq). Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2019a; EPA 2019c; Waste Business Journal [WBJ] 2016; WBJ 2010). More recently, the Environment Research & Education Foundation (EREF) conducted a nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2019a; WBJ 2010). While the number of active MSW landfills has decreased

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[1] For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EREF 2016; EPA 2019b; BioCycle 2010). Regarding industrial waste landfills, the WBJ database (WBJ 2016) includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) of EPA's Greenhouse Gas Reporting Program (GHGRP codified in 40 CFR part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000 and then decreased by 5.7 percent to 213 MMT in 2019 (see Annex 3.14, Table A-221). The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.3 MMT in 2019 (see Annex 3.14, Table A-221). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 14.4 MMT CO_2 Eq. in 2005 to 15.1 MMT CO_2 Eq. in 2019 when accounting for both CH_4 generation and oxidation.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's project and technical database contains certain information on the gas collection and control systems in place at landfills that are a part of the program, which can include the amount of landfill gas collected and flared. In 2020, LMOP identified 9 new landfill gas-to-energy (LFGE) projects (EPA 2020a) that began operation. While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows (EPA 2020b).

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
MSW CH_4 Generation[a]	205.3		-		-	-	-	-	-
Industrial CH_4 Generation	12.1		16.0		16.6	16.6	16.7	16.7	16.7
MSW CH_4 Recovered	(21.3)		-		-	-	-	-	-
MSW CH_4 Oxidized	(18.4)		-		-	-	-	-	-
Industrial CH_4 Oxidized	(1.2)		(1.6)		(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
MSW net CH_4 Emissions (GHGRP)	-		117.0		96.4	93.1	94.4	97.0	99.4
Industrial CH_4 Emissions[b]	10.9		14.4		15.0	15.0	15.0	15.0	15.1
Total	**176.6**		**131.4**		**111.4**	**108.0**	**109.4**	**112.1**	**114.5**

[a] MSW CH$_4$ generation is not estimated after 2005 because the directly reported net CH$_4$ emissions from the GHGRP are used.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2019 (EPA 2020b).

"-" Not applicable due to methodology change.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2019, directly reported net CH$_4$ emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH$_4$ recovered and oxidized for MSW landfills. As such, CH$_4$ generation and CH$_4$ recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Table 7-4: CH$_4$ Emissions from Landfills (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
MSW CH$_4$ Generation[a]	8,214		-		-	-	-	-	-
Industrial CH$_4$ Generation	484		638		665	666	667	668	669
MSW CH$_4$ Recovered	(851)		-		-	-	-	-	-
MSW CH$_4$ Oxidized	(736)		-		-	-	-	-	-
Industrial CH$_4$ Oxidized	(48)		(64)		(66)	(67)	(67)	(67)	(67)
MSW net CH$_4$ Emissions (GHGRP)	-		4,681		3,858	3,722	3,775	3,881	3,978
Industrial net CH$_4$ Emissions[b]	436		575		598	599	600	601	602
Total	**7,063**		**5,255**		**4,456**	**4,321**	**4,375**	**4,482**	**4,580**

[a] MSW CH$_4$ generation is not estimated after 2005 because the directly reported net CH$_4$ emissions from the GHGRP are used.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2019 (EPA 2020b).

"-" Not applicable due to methodology change.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2019, directly reported net CH$_4$ emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. These data incorporate CH$_4$ recovered and oxidized for MSW landfills. As such, CH$_4$ generation and CH$_4$ recovery are not calculated separately. See the Time-Series Consistency section of this chapter for more information.

Methodology

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used to calculate emissions from MSW Landfills.

Methane emissions from landfills are estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH$_4$ generation. The amount of CH$_4$ recovered and combusted from MSW landfills is subtracted from the CH$_4$ generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH$_4$ in a landfill that is oxidized to CO$_2$ as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below and is similar to Equation HH-6 in 40 CFR Part 98.343 for MSW landfills, and Equation TT-6 in 40 CFR Part 98.463 for industrial waste landfills.

$$\text{CH}_{4,\text{MSW}} = (G_{CH4} - \textstyle\sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

CH$_{4,MSW}$	= Net CH$_4$ emissions from solid waste
G$_{CH4,MSW}$	= CH$_4$ generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R	= CH$_4$ recovered and combusted
Ox	= CH$_4$ oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically-validated literature (40 CFR Part 98)

The second method used to calculate CH$_4$ emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH$_4$ from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH$_4$ in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH$_4$ is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH$_4$ in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH$_4$ in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

$$CH_{4,\text{Solid Waste}} = \left[\left(\frac{R}{CE \; x \; f_{REC}} - R \right) x (1 - OX) + R \; x \left(1 - (DE \; x \; f_{Dest}) \right) \right]$$

where,

| CH$_{4,\text{Solid Waste}}$ | = Net CH$_4$ emissions from solid waste |

R	= Quantity of recovered CH$_4$ from Equation HH-4 of EPA's GHGRP
CE	= Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used. (percent)
f$_{REC}$	= fraction of hours the recovery system was operating (percent)
OX	= oxidation factor (percent)
DE	= destruction efficiency (percent)
f$_{Dest}$	= fraction of hours the destruction device was operating (fraction)

The current Inventory uses both methods to estimate CH$_4$ emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional step-wise explanations to generate the net emissions are provided in Annex 3.14.

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills

Annex Steps 1-3		Annex Step 4	Annex Step 5	Annex Step 6
Method US-specific first-order decay (FOD) model		Back-casted EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions
1990 - 2004		**2005 - 2009**	**2010 - 2016**	**2017 - Present**
Parameters IPCC 2006 Emission Factors: • DOC = 0.20 • MCF = 1 • DOC_f = 0.5 • OX = 0.10 • DE = 0.99	Activity Data: • National waste generation data multiplied by the national disposal factor	• Back-casted GHGRP emissions from 2010 to the current reporting year[1,2] • 9% scale-up factor applied to GHGRP emissions	• Net GHGRP emissions[2] • 9% scale-up factor applied to GHGRP emissions	• Net GHGRP emissions[2] • 11% scale-up factor applied to GHGRP emissions

[1] The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2019 (the current reporting year). The back-casted emissions are subject to change in each Inventory based on new reporting year reports and re-submitted greenhouse gas reports for previous years. This method is compatible with the IPCC 2006 Guidelines because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the IPCC 2006 Guidelines or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the IPCC 2006 Guidelines.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 Inventory, only the FOD method was used. Methodological changes were made to the 1990 through 2015 Inventory to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in the Time Series Consistency section of this chapter, Annex 3.14, and a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 through 2018 Inventory estimates for MSW landfills is as follows and is also illustrated in Annex Figure A-18:

- **1940 through 1989:** These years are included for historical waste disposal amounts. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For the Inventory calculations, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in managed, anaerobic landfills (Methane Conversion Factor, MCF, of 1) and those disposed in uncategorized solid waste disposal waste sites (MCF of 0.6) (IPCC 2006). Uncategorized sites represent those sites for which limited information is known about the management practices. All calculations after 1980 assume waste

is disposed in managed, anaerobic landfills. The FOD method was applied to estimate annual CH_4 generation. Methane recovery amounts were then subtracted, and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Step 1.

- **1990 through 2004:** The Inventory time series begins in 1990. The FOD method is exclusively used for this group of years. The national total of waste generated (based on state-specific landfill waste generation data) and a national average disposal factor for 1989 through 2004 were obtained from the State of Garbage (SOG) survey every two years (i.e., 2002, 2004 as published in BioCycle 2006). In-between years were interpolated based on population growth. For years 1989 to 2000, directly reported total MSW generation data were used; for other years, the estimated MSW generation (excluding construction and demolition waste and inerts) were presented in the reports and used in the Inventory. The FOD method was applied to estimate annual CH_4 generation. Landfill-specific CH_4 recovery amounts were then subtracted from CH_4 generation and the result was adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Steps 1 through 3.

- **2005 through 2009:** Emissions for these years are estimated using net CH_4 emissions that are reported by landfill facilities under EPA's GHGRP. Because not all landfills in the United States are required to report to EPA's GHGRP, a 9 percent scale-up factor is applied to the GHGRP emissions for completeness. Supporting information, including details on the technique used to estimate emissions for 2005 to 2009, to develop the scale-up factor, and to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14 Step 4 and in RTI 2018a. A single oxidation factor is not applied to the annual CH_4 generated as is done for 1990 to 2004 because the GHGRP emissions data are used, which already take oxidation into account. The GHGRP allows facilities to use varying oxidation factors (i.e., 0, 10, 25, or 35 percent) depending on their facility-specific calculated CH_4 flux rate. The average oxidation factor from the GHGRP facilities is 19.5 percent (from reporting years 2011 to 2017). A detailed explanation of the methods used to develop the back-casted emissions and revised scale-up factor are presented in Annex 3.14 Step 4.

- **2010 through 2016:** Net CH_4 emissions as directly reported to the GHGRP are used with a 9 percent scale-up factor to account for landfills that are not required to report to the GHGRP. A combination of the FOD method and the back-calculated CH_4 emissions were used by the facilities reporting to the GHGRP. Landfills reporting to the GHGRP without gas collection and control apply the FOD method, while most landfills with landfill gas collection and control apply the back-calculation method. As noted above, GHGRP facilities use a variety of oxidation factors. The average oxidation factor from the GHGRP facilities is 19.5 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 5.

- **2017 through 2019:** The same methodology is applied as for 2010 through 2016 where a scale-up factor is applied to account for landfills that are not required to report to the GHGRP. The scale-up factor was revised for the current (1990 to 2019) Inventory to incorporate facilities that have stopped reporting to the GHGRP, new additions to the 2020 LMOP Database (EPA 2020a), and corrections to the underlying database of non-reporting landfills used to develop the 9 percent scale-up factor that were identified. For 2017 to 2019, a scale-up factor of 11 percent is applied annually to the GHGRP net reported CH_4 emissions. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 6.

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in the Time-Series Consistency section of this chapter and in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model. Activity data used are industrial production data (ERG 2020) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the IPCC 2006 Guidelines and are the same across the entire time series.

The FOD equation from IPCC 2006 is used via the waste model to estimate methane emissions:

$$CH_{4,IND} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,\text{Solid Waste}}$	= Net CH_4 emissions from solid waste
$G_{CH4,\text{Ind}}$	= CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R	= CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX	= CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the IPCC 2006 Guideline value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. EPA's GHGRP provides some insight into waste disposal in industrial waste landfills but is not comprehensive. Data reported to the GHGRP on industrial waste landfills suggests that most of the organic waste which would result in methane emissions is disposed at pulp and paper and food processing facilities. Of the 168 facilities that reported to Subpart TT of the GHGRP in 2019, 92 (54 percent) are in the North American Industrial Classification System (NAICS) for Pulp, Paper, and Wood Products (NAICS 321 and 322) and 12 (7 percent) are in Food Manufacturing (NAICS 311).

Based on this limited information, the Inventory methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors. EPA validated this assumption through an analysis of the Subpart TT of the GHGRP in the 2016 reporting year (RTI 2018b). The Subpart TT waste disposal information for pulp and paper facilities correlates well with the activity data currently used to estimate Inventory emissions; however, the waste disposal information in Subpart TT related to food and beverage facilities are approximately an order of magnitude different than the Inventory disposal estimates for the entire time series.

EPA conducted a literature review in 2020 to investigate other sources of industrial food waste, which is briefly described in the Planned Improvements section, and decided to maintain the currently used methodology for the 1990-2019 Inventory due to questions around data availability across the 1990 to 2019 time series, the completeness and representativeness of other estimates and methodologies, and the level of effort required to reproduce and/or merge estimates across the 1990 to 2019 time series.

The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only one of the 168 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2020b). However, because EPA's GHGRP is not a national database and comprehensive data regarding gas collection systems have not been published for industrial waste landfills, assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills have not been made for the Inventory methodology.

The amount of CH_4 oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted (and later land applied), combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the Inventory has used:

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* reports use a materials flow methodology, commonly referred to as a 'top-down' methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, other food management pathways, or landfilled nationwide. The amount of MSW generated is estimated by estimating production and then adjusting these values by addressing the imports and exports of produced materials to other countries. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (U.S. EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials/biochemical processing (i.e., rendering); codigestion/anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer/wastewater treatment.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report. Emissions from anaerobic digesters are presented in three different sections depending on the digester category. Emissions from on-farm digesters are included in the Agriculture sector; emissions from digesters at wastewater treatment plants emissions from stand-alone digesters are presented in separate sections in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this Inventory is not facility-specific modeling and while this approach may over- or under-estimate CH_4 generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2019, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018a), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2019. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

With regard to the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time-Series Consistency* (IPCC 2006), "the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years" (IPCC 2006). This chapter, however, recommends against back-casting emissions back to 1990 with a limited set of data and instead provides guidance on techniques to splice, or join methodologies together. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data becomes available for multiple years. This was the case with the GHGRP data for MSW landfills, where directly reported CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC's good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using the FOD method from 1990 to 2009, or using the FOD method for a portion of that time and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. A detailed explanation and a chart showing the estimates across the time series considering the two method options is included in Annex 3.14. EPA

ultimately decided to back-cast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC *Good Practice Guidance* for ensuring time series consistency.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the Inventory for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2004; whereas directly reported CH_4 emissions, which accounts for CH_4 recovery, is used for facilities reporting to the GHGRP for years 2005 to 2018. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 through 2013 Inventory report (two years before the full GHGRP data set started being used for net CH_4 emissions for the Inventory). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. Additionally, the methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered.

The LFGE database was updated annually until 2015. The flare database was populated annually until 2015 by the voluntary sharing of flare sales data by select vendors, which likely underestimated recovery for landfills not included in the three other recovery databases used by the Inventory. The EIA database has not been updated since 2006 and has, for the most part, been replaced by the GHGRP MSW landfills database. To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the Inventory methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation

estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**114.5**	**88.0**	**140.0**	**-22%**	**+23%**
MSW	CH_4	99.4	74.1	124.5	-25%	+25%
Industrial	CH_4	15.1	10.4	18.9	-31%	+25%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Vol. 1, Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the Inventory data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the Inventory dataset to ensure they are appropriately collected and are reliable;
- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this Inventory, because new data were not added to the recovery databases in this Inventory year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA

are accurate, complete, and consistent.[2] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

For the current (1990 to 2019) Inventory, the scale-up factor was revised from 9 percent to 11 percent resulting from additional QC checks performed on the underlying 2016 Non-Reporting Landfills Database used to develop the 9 percent scale-up factor, the addition of the total waste-in-place for the 194 landfills no longer reporting to Subpart HH, changes to the waste-in-place for some landfills in the 2020 LMOP Database, and the increase in estimated annual waste disposed between 2016 and 2018 for all non-reporting landfills in the database. Overall, the estimated waste-in-place for non-reporting landfills increased by approximately 274 million MT. The estimates of waste-in-place for the non-reporting landfills should be considered best estimates based on available data from the 2020 LMOP Database (EPA 2020a) and the 2016 WBJ Directory (WBJ 2016). No efforts were made in developing the 2018 Non-Reporting Landfills Database to contact facilities to verify the information included in either source database.

Additional QC checks on the 2016 Non-Reporting Landfills Database increased the total waste-in-place estimated for 2016 by 38 million MT. Specifically, QC checks and corrections made to the underlying 2016 Non-Reporting Landfills Database resulted in an increase of 38 million tons of waste-in-place resulting from a formula error that under-estimated the waste-in-place for some landfills with a permitted end year after 2016, especially for those landfills that had reported closure dates in 2030 or later. The year that the waste-in-place data were from in the 2017 LMOP Database, a primary source used, was not pulled into the 2016 Non-Reporting Landfills Database, thus the methodology assumed that all waste-in-place data were from 2016. The waste-in-place year is now included in the 2018 Non-Reporting Landfills Database, allowing for a more realistic waste-in-place value to be estimated by landfill.

Several quality control checks were performed on the 2018 Non-Reporting Landfills Database used to calculate the 11 percent scale-up factor. Specific checks included a 10 percent check of the data carried over from the 2016 WBJ Directory and the LMOP Databases, randomly checking formula calculations, comparing the 2017 and 2020 LMOP Databases for changes in waste-in-place, and sorting the estimated waste-in-place column from largest to smallest to identify errors in the larger landfills.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. These recalculations increased net emissions for MSW landfills from 2005 to 2015 by less than 0.5 percent when compared to the previous Inventory report. Each Inventory year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH

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[2] See <https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf>.

annual greenhouse gas reports resubmitted for 2015 to 2018 slightly increased or decreased total Subpart HH reported net emissions by +/- 0.3 percent in the years the Subpart HH data are applied (i.e., 2005 to 2019). No Subpart HH reports were resubmitted for the 2010 to 2014 reporting years that resulted in net emission changes. These changes resulted in changes to the net Inventory emissions ranging from -0.03 percent to +0.06 percent. A change in net Subpart HH reported emissions results in the same percentage change in the Inventory emissions for that year.

The scale-up factor was also reassessed as a planned improvement for the current (1990 to 2019) Inventory. Results from this effort increased the scale-up factor from 9 percent to 11 percent. The scale-up factor increased because of the inclusion of 194 GHGRP Subpart HH facilities that have off-ramped, a calculation error identified for some non-reporting landfills when developing the 9 percent scale-up factor in 2016, and changes to the estimated waste-in-place for all non-reporting landfills since 2016. The 9 percent scale-up factor is being retained and used for 2005-2016 and the 11 percent is being used for 2017 to 2019.

Using the 11 percent scale-up factor, in addition to revisions to the previously submitted GHGRP reports between 2015 to 2018 ultimately increased net CH_4 emissions by 1.6 percent in 2017 (1.7 MMT CO_2 Eq.) and 1.4 percent in 2018 (1.5 MMT CO_2 Eq.) compared to the previous (1990 to 2018) Inventory.

Planned Improvements

EPA has received recommendations from industry stakeholders regarding the DOC values and decay rates (k value) required to be used in the GHGRP calculations based on recent trends in the composition of waste disposed in MSW landfills. Stakeholders have suggested that newer, more up-to-date default values for both k and DOC in the GHGRP could then be reflected in the 2005 and later years of the Inventory. In response, EPA is developing a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform future GHGRP rulemaking where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the Inventory emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR part 98.

EPA is investigating the k values for the three climate types (dry, moderate, and wet) against new data and other landfill gas models, and how they are applied to the percentage of the population assigned to these climate types. EPA will also assess the uncertainty factor applied to these k values in the Waste Model.

With respect to the scale-up factor, EPA will periodically assess the impact to the waste-in-place and emissions data from facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the "off-ramp" provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). As was the case with this Inventory, if warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory. The methodology applied to develop the scale-up factor will be reviewed for the 1990 to 2020 inventory cycle to determine whether the total waste-in-place for all landfills in the Non-Reporting Landfills Database should be factored into the scale-up factor, or a subset of years (e.g., 25, 30, 50) depending on the duration of operation.

EPA began investigating the prevalence of food-related waste deposited into industrial waste landfills in 2020 and will record the findings from this exercise in a memorandum. The resources identified with the most relevant data for the Inventory include the EPA's 2020 Wasted Food Measurement Methodology Scoping Memo (EPA 2020c); the Food Waste Reduction Alliance survey reports on the industrial food manufacturing sector conducted to date for 2012 (BSR 2013), 2013 (BSR 2014), and 2015 (FWRA 2016); and one peer-reviewed journal article entitled, Assessing U.S. food wastage and opportunities for reduction (Dou et al. 2016). EPA's wasted food measurement methodology includes estimates for industrial food waste based on others' research estimates, but industrial food waste estimates will not be incorporated into the EPA's Advancing Sustainable Materials reports because industrial waste is beyond the scope of these reports. Dou et al. (2016) primarily used findings from the Food Waste Reduction Alliance surveys, which received survey data from a handful of facilities and may not be representative

of the entire U.S. food and beverage sector. EPA has decided to maintain the currently applied methodology to estimate emissions from the industrial food and beverage sector for the current Inventory cycle.

Additionally, with the recent publication of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019), EPA will begin to update applicable emission factors, methodologies, and assumptions underlying emission estimates for landfills and make any applicable changes during the next (1990 to 2020) Inventory cycle per the *2019 Refinement*.

Box 7-4: Overview of U.S. Solid Waste Management Trends

As shown in Figure 7-4 and Figure 7-5, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018

Management of MSW in the United States

- MSW to WTE 12%
- Other Food Management 6%
- Composted 8%
- Recycled 24%
- Landfilled 50%
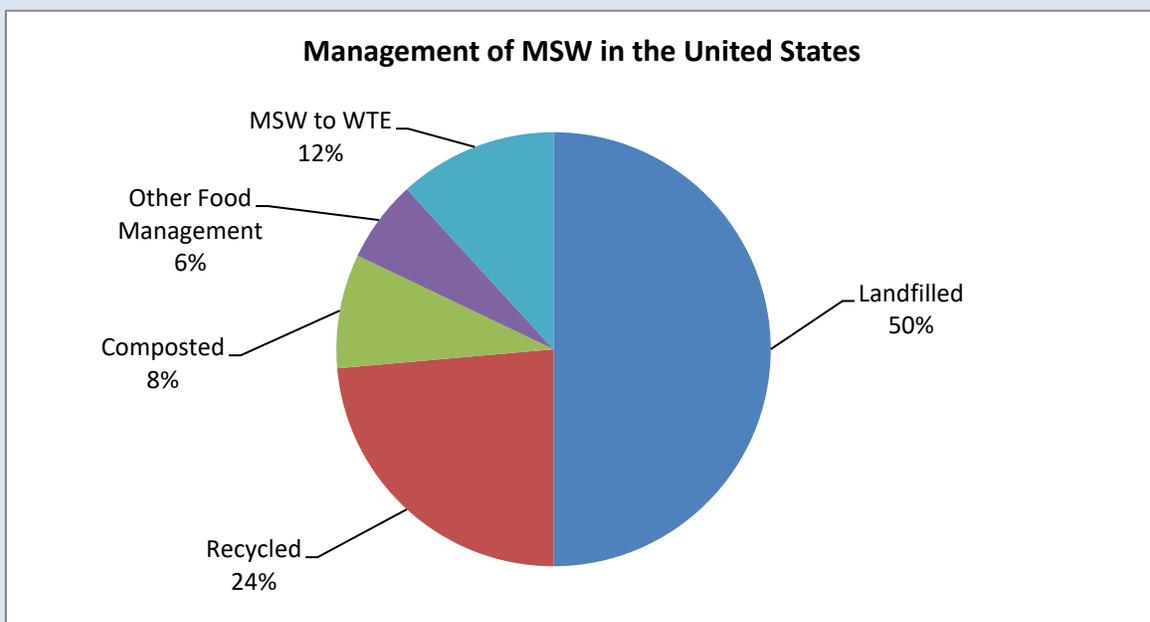
Source: EPA (2020d)

Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA 2020a. MSW to WTE is combustion with energy recovery (WTE = waste to energy).

Figure 7-5: MSW Management Trends from 1990 to 2018
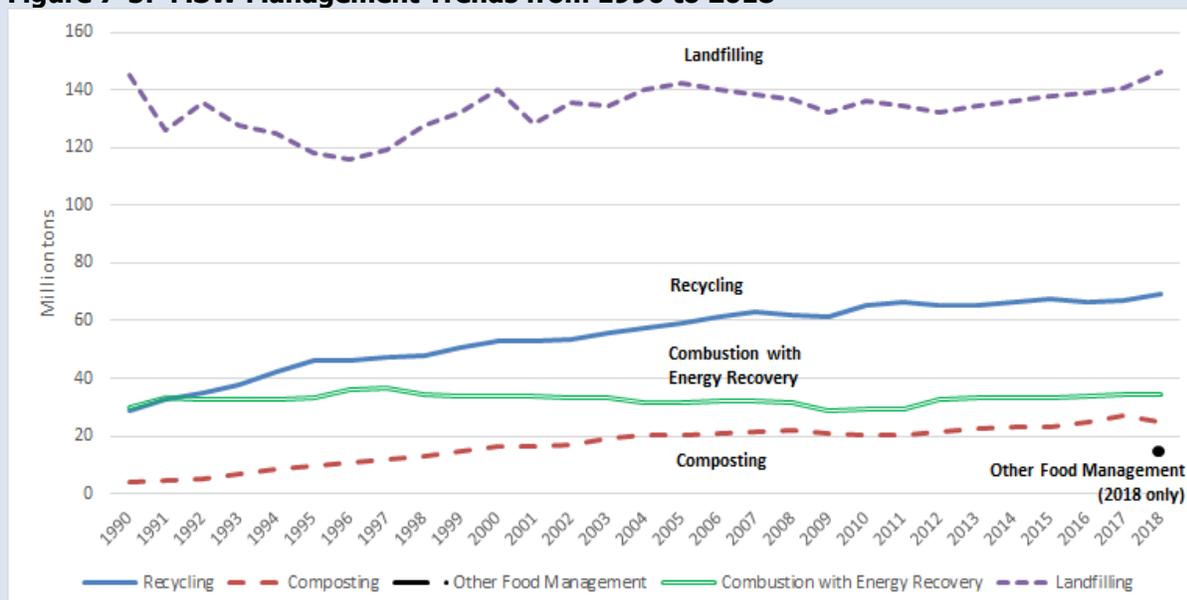
Source: EPA (2020d). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020d for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA 2019c for 2010 and 2016. Data were taken from EPA 2018 for 2014. Data were taken from Table 35 of EPA 2016b for 2012 and 2013. Data were taken from Table 30 of EPA 2014 for 2008 and 2011. The reports with data available for years prior to EPA 2012 can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site < https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management>.
Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the 'Other Food Management' category.

Table 7-6 presents a typical composition of waste disposed of at a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Due to China's recent ban on accepting certain kinds of solid waste by the end of 2017 (WTO 2017), inclusive of some paper and paperboard waste, plastic waste, and other miscellaneous inorganic wastes, there has been a slight increase in the disposal of paper and paperboard and plastic wastes since 2017 (Table 7-6). EPA expects these numbers to continuing increasing until new markets for recycling of these goods are identified.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%

Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%
Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020d)

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)

Source: EPA (2020d). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020d for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA 2019c for 2010 and 2016. Data were taken from EPA 2018 for 2014. Data were taken from Table 35 of EPA 2016b for 2012 and 2013. Data were taken from Table 30 of EPA 2014 for 2008 and 2011. The reports with data available for years prior to EPA 2012 can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management web site <https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management>.

Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28% of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting).

7.2 Wastewater Treatment and Discharge (CRF Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter,

suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[3] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 18 percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2017). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants, or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment.

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though it is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge).

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g., nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

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[3] Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released (Short et al. 2014; Short et al. 2017), and the addition of organic matter or nitrogen from wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2019, CH_4 emissions from domestic wastewater treatment and discharge were estimated to be 10.3 MMT CO_2 Eq. (410 kt CH_4) and 1.8 MMT CO_2 Eq. (72 kt CH_4), respectively. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004a; U.S. Census Bureau 2017). In 2019, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 6.4 MMT CO_2 Eq. (254 kt CH_4). Industrial emission sources have generally increased across the time series through 1994 and then fluctuated up and down with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have seen an uptick since 2017. Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, emissions from domestic wastewater treatment and discharge in 2019 were estimated to be 20.5 MMT CO_2 Eq. (69 kt N_2O) and 5.3 MMT CO_2 Eq. (18 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 25.8 MMT CO_2 Eq. (87 kt N_2O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption. In 2019, N_2O emissions from industrial wastewater treatment were estimated to be 0.6 MMT CO_2 Eq. (2 kt N_2O). Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, petroleum refining, and brewery industries. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
CH_4	**20.2**	**20.1**	**18.8**	**18.7**	**18.5**	**18.4**	**18.4**
Domestic Treatment	13.5	13.0	11.2	10.9	10.5	10.4	10.3
Domestic Effluent	1.2	1.2	1.8	1.8	1.8	1.8	1.8
Industrial[a] Treatment	4.9	5.4	5.4	5.6	5.7	5.8	5.9
Industrial[a] Effluent	0.5	0.5	0.4	0.4	0.4	0.4	0.4
N_2O	**18.7**	**23.0**	**25.4**	**25.9**	**26.4**	**26.1**	**26.4**

	13.6		17.7		19.5	19.9	20.4	20.3	20.6
Domestic Treatment	13.6		17.7		19.5	19.9	20.4	20.3	20.6
Domestic Effluent	4.7		4.8		5.4	5.4	5.4	5.3	5.3
Industrialb Treatment	0.4		0.4		0.5	0.5	0.5	0.5	0.5
Industrialb Effluent	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Total	**38.9**		**43.1**		**44.2**	**44.6**	**44.9**	**44.5**	**44.8**

Note: Totals may not sum due to independent rounding.

a Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

b Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
CH_4	**806**		**803**		**753**	**747**	**739**	**737**	**736**
Domestic Treatment	540		518		447	434	421	416	410
Domestic Effluent	49		49		71	72	72	72	72
Industriala Treatment	196		215		217	223	228	232	236
Industriala Effluent	21		19		18	18	18	18	18
N_2O	**63**		**77**		**85**	**87**	**89**	**88**	**88**
Domestic Treatment	46		59		65	67	69	68	69
Domestic Effluent	16		16		18	18	18	18	18
Industrialb Treatment	1		1		2	2	2	2	2
Industrialb Effluent	+		+		+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

a Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

b Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Methodology

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge. Domestic wastewater treatment follows the IPCC Tier 1 methodology, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors. Industrial wastewater treatment and discharge follow IPCC Tier 1 methodologies.

IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been previously estimated, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from

anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

$$\text{Total Domestic } CH_4 \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D + E$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2019.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2019, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	232	5.8	48.1
Centrally-Treated Aerobic Systems (B)	36	0.9	7.5
Centrally-Treated Anaerobic Systems (C)	134	3.3	27.7
Anaerobic Sludge Digesters (D)	8.1	0.2	1.7
Centrally-Treated Wastewater Effluent (E)	72	1.8	15.0
Total	**482**	**12.1**	**100**

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 18 percent in 2019; U.S. Census Bureau 2017) and an emission factor and then converting the result to kt/year.

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2020) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 7-12 presents U.S. population for 1990 through 2019. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2017). Methane emissions for septic systems are estimated as follows:

$$\textit{Emissions from Septic Systems} \text{ (U.S. Specific)} = A$$
$$= US_{POP} \times (T_{SEPTIC}) \times (EF_{SEPTIC}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	1990-2019: U.S. Census Bureau (2020)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017)

Variable	Variable Description	Units	Inventory Years: Source of Value
			Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2019: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents total BOD_5 produced (also referred to as the total organically degradable material in wastewater or TOW) for 1990 through 2019. The BOD_5 production rate was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Total wastewater BOD_5 produced per capita (U.S. Specific (ERG 2018a), kg/capita/day)

$$BOD_{\text{gen rate}} = BOD_{\text{without scrap}} \times (1 - \%\text{disposal}) + BOD_{\text{with scraps}} \times (\%\text{disposal})$$

Total organically degradable material in domestic wastewater (IPCC 2019 (Eq. 6.3), Gg/year)

$$TOW = US_{POP} \times BOD_{\text{gen rate}} \times 365.25$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{\text{gen rate}}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2019: Calculated
$BOD_{\text{without scrap}}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003)
$BOD_{\text{with scraps}}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	2004-2013: Linear interpolation 2014-2019: Metcalf & Eddy (2014)
% disposal	Percent of housing units with kitchen disposal[a]	%	1990-2013: U.S. Census Bureau (2013) 2014-2019: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2019: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	1990-2019: U.S. Census Bureau (2020)
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater BOD₅ Produced (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Population	253		300		325	327	329	331	334
TOW	8,131		9,624		9,736	9,820	9,896	9,971	10,079

Sources: U.S. Census Bureau (2020); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD₅) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 82 percent in 2019), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands), constructed wetlands only, and anaerobic systems, and the emission factor[4] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[5] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC methodology (IPCC 2019) and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4 recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

$$Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (other\ than\ Constructed\ Wetlands)\ (B1) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ Only)\ (B2) + Emissions\ from\ Centrally\ Treated\ Aerobic\ Systems\ (Constructed\ Wetlands\ used\ as\ Tertiary\ Treatment)\ (B3) = B$$

where,

$$Total\ organics\ in\ centralized\ wastewater\ treatment\ (IPCC\ 2019\ (Eq.\ 6.3A),\ Gg\ BOD/year)$$
$$TOW_{CENTRALIZED} = TOW \times T_{CENTRALIZED} \times I_{COLLECTED}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2019: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation

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[4] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B₀, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019) and constructed wetlands (0.4) (IPCC 2014).

[5] Throughout this document, the term "sludge" refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. "Biosolids" refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

			2018-2019: Forecasted from the rest of the time series
I$_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2019: IPCC (2019)

[a] Value of this activity data varies over the time series.

Organic component removed from aerobic wastewater treatment (IPCC 2019 (Eq. 6.3B), Gg/year)

$$S_{aerobic} = S_{mass} \times [(\% \text{ aerobic w/primary} \times K_{rem,aer\_prim}) + (\% \text{ aerobic w/out primary} \times K_{rem,aer\_noprim}) + (\% \text{aerobic+digestion} \times K_{rem,aer\_digest})] \times 1000$$

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 (Eq. 6.1), kt CH_4/year) = B1

$$= [(TOW_{CENTRALIZED}) \times (\% \text{ aerobic}_{OTCW}) - S_{aerobic}] \times EF_{aerobic} - R_{aerobic}$$

Table 7-14: Variables and Data Sources for CH$_4$ Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH$_4$/year)			
S$_{aerobic}$	Organic component removed from aerobic wastewater treatment	Gg BOD/year	1990-2019: Calculated
S$_{mass}$	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007) 1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2019: Forecasted from the rest of the time series
% aerobic$_{OTCW}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2019: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion	%	
K$_{rem,aer\_prim}$	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2019: IPCC (2019)
K$_{rem,aer\_noprim}$	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	
K$_{rem,aer\_digest}$	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
1000	Conversion factor	metric tons to kilograms	
EF$_{aerobic}$	Emission factor – aerobic systems (0.018)	kg CH$_4$/kg BOD	

Variable	Variable Description	Units	Inventory Years: Source of Value
$R_{aerobic}$	Amount CH$_4$ recovered or flared from aerobic wastewater treatment (0)	kg CH$_4$/year	

[a] Value of this activity data varies over the time series.

Constructed wetlands exhibit both aerobic and anaerobic treatment (partially anaerobic treatment) but are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A BOD$_5$ concentration of 30 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. These standards are based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)} \text{ (IPCC 2014 (Eq. 6.1), kt}$$
$$CH_4/year) = B2$$
$$= [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\text{aerobic}_{\text{CW}})] \times (\text{EF}_{\text{CW}})$$

$$\textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)} \text{ (U.S.}$$
$$\text{Specific, kt } CH_4/year) = B3$$
$$= [(\text{POTW\_flow\_CW}) \times (\text{BOD}_{\text{CW,INF}}) \times 3.785 \times (\text{EF}_{\text{CW}})] \times 1/10^6 \times 365.25$$

Table 7-15: Variables and Data Sources for CH₄ Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH₄/year)			
TOW$_{\text{CENTRALIZED}}$	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
% aerobic$_{\text{CW}}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
EF$_{\text{CW}}$	Emission factor for constructed wetlands	kg CH$_4$/kg BOD	1990-2019: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH₄/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation.

Variable	Variable Description	Units	Inventory Years: Source of Value
			2013-2019: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (30)	mg/L	1990-2019: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2019: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 (Eq. 6.1), kt CH_4/year) = C

$$= [(TOW_{CENTRALIZED}) \times (\% \text{ anaerobic}) - S_{anaerobic}] \times EF_{anaerobic} - R_{anaerobic}$$

Table 7-16: Variables and Data Sources for CH₄ Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH₄/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2019: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2019: IPCC (2019)
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Emissions from Anaerobic Sludge Digesters (U.S. Specific, kt CH_4/year) = D

$$= [(POTW\_flow\_AD) \times (\text{biogas gen})/(100)] \times 0.0283 \times (FRAC\_CH_4) \times 365.25 \times (662) \times (1-DE) \times 1/10^9$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH₄/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2019: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2019: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2019: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
FRAC_CH₄	Proportion of Methane in Biogas (0.65)	No units	1990-2019: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2019: EPA (1993a)
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2019: EPA (1998); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

$$\textit{Emissions from Centrally Treated Systems Discharge} \text{ (U.S. Specific, kt CH}_4\text{/year)} = E$$
$$= (TOW_{RLE} \times EF_{RLE}) + (TOW_{Other} \times EF_{Other})$$

where,

$$\textit{Total organics in centralized treatment effluent} \text{ (IPCC 2019 (Eq. 6.3D), Gg BOD/year)} = TOW_{EFFtreat,CENTRALIZED}$$
$$= [TOW_{CENTRALIZED} \times \% \text{ primary} \times (1\text{-}TOW_{rem,PRIMARY})] + [TOW_{CENTRALIZED} \times \% \text{ secondary} \times (1\text{-}TOW_{rem,SECONDARY})] + [TOW_{CENTRALIZED} \times \% \text{ tertiary} \times (1\text{-}TOW_{rem,TERTIARY})]$$

$$\text{Total organics in effluent discharged to reservoirs, lakes, or estuaries (U.S. Specific, Gg BOD/year)} = TOW_{RLE}$$
$$= TOW_{EFFtreat,CENTRALIZED} \times Percent_{RLE}$$

$$\text{Total organics in effluent discharged to other waterbodies (U.S. Specific, Gg BOD/year)} = TOW_{Other}$$
$$= TOW_{EFFtreat,CENTRALIZED} \times Percent_{Other}$$

Table 7-18: Variables and Data Sources for CH₄ Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
TOW$_{EFFtreat,CENTRALIZED}$	Total organics in centralized treatment effluent	Gg BOD/year	1990-2019: Calculated
TOW$_{CENTRALIZED}$	Total organics in centralized wastewater treatment	Gg BOD/year	1990-2019: Calculated
% primary	Percent of primary domestic centralized treatment	%	1990,1991: Set equal to 1992.
% secondary	Percent of secondary domestic centralized treatment	%	
% tertiary	Percent of tertiary domestic centralized treatment	%	1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
TOW$_{rem,PRIMARY}$	Fraction of organics removed from primary domestic centralized treatment	No units	
TOW$_{rem,SECONDARY}$	Fraction of organics removed from secondary domestic centralized treatment	No units	1990-2019: IPCC (2019)
TOW$_{rem,TERTIARY}$	Fraction of organics removed from tertiary domestic centralized treatment	No units	
TOW$_{RLE}$	Total organics in effluent discharged to reservoirs, lakes, and estuaries	Gg BOD/year	1990-2019: Calculated
TOW$_{Other}$	Total organics in effluent discharge to other waterbodies	Gg BOD/year	
EF$_{RLE}$	Emission factor (discharge to reservoirs/lakes/estuaries)	kg CH₄/kg BOD	1990-2019: IPCC (2019)
EF$_{Other}$	Emission factor (discharge to other waterbodies)	kg CH₄/kg BOD	
Percent$_{RLE}$	% discharged to reservoirs, lakes, and estuaries	%	1990-2010: Set equal to 2010
Percent$_{Other}$	% discharged to other waterbodies	%	2010: ERG (2021) 2011: Obtained by linear interpolation 2012: ERG (2021) 2013-2019: Set equal to 2012

Industrial Wastewater CH₄ Emission Estimates

Industrial wastewater CH₄ emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH₄ will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify U.S. industries likely to generate CH_4 are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2019 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2019, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.0	78.5
Pulp & Paper	0.7	11.4
Fruit & Vegetables	0.2	3.6
Ethanol Refineries	0.2	2.5
Breweries	0.1	2.2
Petroleum Refineries	0.1	1.8
Total	**6.4**	**100**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

The general IPCC equation to estimate methane emissions from each type of treatment system used for each industrial category is:

$$CH_4 \text{ (industrial sector)} = [(TOW_i - S_i) \times EF - R_i]$$

where,

CH_4 (industrial sector)	= Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
i	= Industrial sector
TOW_i	= Total organics in wastewater for industrial sector i (kg COD/year)
S_i	= Organic component removed from aerobic wastewater treatment for industrial sector i (kg COD/year)
EF	= System-specific emission factor (kg CH_4/kg COD)
R_i	= Methane recovered for industrial sector I (kg CH_4/year)

The general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category is:

$$TOW_i = P_i \times W_i \times COD_i$$

where,

TOW_i	= Total organically degradable material in wastewater for industry I (kg COD/yr)
i	= Industrial sector
P_i	= Total industrial product for industrial sector i (t/yr)
W_i	= Wastewater generated (m^3/t product)
COD_i	= Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21. For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic.

Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as "anaerobic", wastewater treated in aerated stabilization basins or facultative lagoons were classified as "ASB" (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as "aerobic/other."

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

$$S_{pulp,asb} = TOW_{pulp} \times \% \text{ removal w/primary}$$

where,

$S_{pulp,asb}$	= Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp}	= Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary	= Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$	= Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass}	= Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem}	= Sludge factor (kg BOD/kg sludge)
10^{-6}	= Conversion factor, kilograms to Gigagrams

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass}	= Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim}	= Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer}	= Sludge production from secondary aerobic treatment (kg sludge/m^3)
P	= Production (t/yr)
W	= Wastewater Outflow (m^3/t)

Default emission factors[6] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol Production	Breweries	Petroleum Refining
1990	83.6	27.3	14.6	38.7	2.5	23.9	702.4
2005	92.4	31.4	25.1	42.9	11.7	23.1	818.6
2015	80.9	32.8	27.7	44.6	44.2	22.4	914.5
2016	79.9	34.2	28.3	43.5	45.8	22.3	926.0
2017	80.3	35.4	28.9	42.9	47.2	21.8	933.5
2018	79.4	36.4	29.4	42.6	48.0	21.5	951.4
2019	78.8	37.4	30.1	43.1	47.2	21.1	940.2

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.
Sources: Pulp and Paper - FAO (2020a) and FAO (2020b); Meat, Poultry, and Vegetables - USDA (2020a and 2020c); Ethanol - Cooper (2018) and RFA (2020a and 2020b); Breweries - Beer Institute (2011) and TTB (2020); Petroleum Refining - EIA (2020).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2019)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.09	--	17.6	1.67
Breweries – NonCraft	1.94	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.
[b] Units are COD (g/L).
Sources: Pulp and Paper (BOD, COD:BOD) - Malmberg (2018); Meat and Poultry (Outflow, BOD) - EPA (2002); Meat and Poultry (COD:BOD) - EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) - EPA (1997a); Ethanol Production – Wet Mill (Outflow) - Donovan (1996), NRBP (2001), Ruocco (2006a); Ethanol Production – Wet Mill (BOD) - White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) - Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) - EPA (1997a); Petroleum Refining (Outflow) - ERG (2013b); Petroleum Refining (COD) - Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2017); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) - Brewers Association (2016b).

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[6] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019).

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically	
				% Treated in ASBs	% Treated in Other Aerobic
Pulp and Paper	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[1]	33	0	33
Poultry Processing	25	25[1]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	0	0	0
Ethanol Production – Dry Mill	75	75	0	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries - NonCraft	100	99	1	0	1

[1] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.
Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.
Sources: ERG (2008b); ERG (2013a); ERG (2013b); ERG (2021).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry		
	Pulp and Paper	Fruit/Vegetable Processing	Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m³)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production - Metcalf & Eddy (2003); Sludge factors – IPCC (2019).

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

$$CH_4 \text{ Effluent}_{IND} = TOW_{EFFLUENT,IND} \times EF_{EFFLUENT}$$

where,

$CH_4 \text{ Effluent}_{IND}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($TOW_{EFFLUENT,industry}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries.

Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

$$TOW_{EFFLUENT,IND} = TOW_{IND} * \%onsite * (1 - TOW_{REM})$$

where,

$TOW_{EFFLUENT,IND}$	= Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
TOW_{IND}	= Total organics in untreated wastewater for industry (kg COD/year)
%onsite	= Percent of industry wastewater treated on site (%)
TOW_{REM}	= Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.905	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp and Paper. Wastewater treatment for the pulp and paper industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2019 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000 through 2003, and 2010 through 2018. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2020a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999

was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2019 was forecasted from the rest of the time series. A time series of the overall wastewater outflow is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018). Data for intervening years were obtained by linear interpolation, while 2017 to 2019 were forecasted from the rest of the time series. The average BOD concentrations in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2019 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Year	Wastewater Outflow (m^3/ton)
1990	68
2005	43
2015	40
2016	40
2017	39
2018	38
2019	38

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH$_4$/kg COD for anaerobic lagoons were used to estimate the CH$_4$ produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH$_4$/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Other Vegetables	9.93	0.755
Fruit		
Apples	9.09	8.17
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically. A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[7] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

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[7] Available online at <https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector>.

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 7,000 (Brewers Association 2020). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to the present (TTB 2020). For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2019.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high-strength wastewater from particular brewing processes (known as "side streaming") to a POTW, greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

$$\text{Total Domestic } N_2O \text{ Emissions from Wastewater Treatment and Discharge (kt)} = A + B + C + D$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2019.

Table 7-27: Domestic Wastewater N$_2$O Emissions from Septic and Centralized Systems (2019, kt, MMT CO$_2$ Eq. and Percent)

	N$_2$O Emissions (kt)	N$_2$O Emissions (MMT CO$_2$ Eq.)	% of Domestic Wastewater N$_2$O
Septic Systems	3	0.9	3.5
Centrally-Treated Aerobic Systems	66	19.6	76.1
Centrally-Treated Anaerobic Systems	0	0.0	0
Centrally-Treated Wastewater Effluent	18	5.3	20.4
Total	**87**	**25.8**	**100**

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

$$\text{Annual per capita protein supply (U.S. Specific, kg/person/year)} = \text{Protein}_{\text{SUPPLY}}$$
$$= \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

$$\text{Consumed Protein (IPCC 2019 (Eq. 6.10A), kg/person/year)} = \text{Protein}$$
$$= \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
Protein$_{\text{SUPPLY}}$	Annual per capita protein supply	kg/person/year	1990-2019: Calculated
Protein$_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2019: USDA (2020b)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2020b) 2011-2017: FAO (2020c) and scaling factor 2018, 2019: Forecasted from the rest of the time series

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 18 percent in 2019; U.S. Census Bureau 2017), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. All factors obtained from IPCC (2019).

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2020) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2017). The methodological equations are:

$$\textit{Total nitrogen entering septic systems} \text{ (IPCC 2019 (Eq. 10), kg N/year)} = \text{TN}_{\text{DOM\_SEPTIC}}$$
$$= (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

$$Emissions\ from\ Septic\ Systems\ (\text{IPCC 2019 (Eq. 6.9))} = A$$
$$= TN_{DOM\_SEPTIC} \times (EF_{SEPTIC}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
TN_{DOM_SEPTIC}	Total nitrogen entering septic systems	kg N/year	1990-2019: Calculated
US_{POP}	U.S. population[a]	Persons	1990-2019: U.S. Census Bureau (2020)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.016)	kg N/kg protein	1990-2019: IPCC (2019)
N_{HH}	Additional nitrogen from household products (1.17)	No units	
$F_{IND-COM\_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	
$F_{NON-CON\_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 82 percent in 2019), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Non-consumed protein in centralized wastewater treatment for the U.S. was determined by dividing the per capita total Kjeldahl nitrogen (TKN) loading (estimated by multiplying the influent nitrogen concentration by the wastewater flow to centralized wastewater treatment divided by the population using centralized wastewater treatment) by the nitrogen from protein (estimated by multiplying the fraction of N in protein [IPCC 2019] by the annual per capita protein supply [FAO 2020c]).

$$Factor\ for\ Non\text{-}Consumed\ Protein\ (\text{U.S. Specific}) = F_{NON\text{-}CON}$$
$$= [(N_{INF} \times Flow_{US} \times 3.785 \times 365.25)/(US_{POP} \times T_{CENTRALIZED})]/(Protein_{SUPPLY} \times F_{NPR})$$

$$Total\ nitrogen\ entering\ centralized\ systems\ (\text{IPCC 2019 (Eq. 10), kg N/year}) = TN_{DOM\_CENTRAL}$$
$$= (US_{POP} \times T_{CENTRALIZED}) \times Protein \times F_{NPR} \times N_{HH} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
$F_{NON-CON}$	Factor for U.S. specific non-consumed protein	No units	1990-2019: Calculated
N_{INF}	Influent Nitrogen Concentration (40)	mg/L	1990-2019: Metcalf & Eddy (2014)
$Flow_{US}$	Wastewater Flow to Centralized Wastewater Treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation 2013-2019: Forecasted from the rest of the time series
3.785	Conversion factor	liters to gallons	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
US_{POP}	U.S. population[a]	Persons	1990-2019: U.S. Census Bureau (2020)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2017: U.S. Census Bureau (2017) Data for intervening years obtained by linear interpolation 2018 and 2019: Forecasted from the rest of the time series
$Protein_{SUPPLY}$	Annual per capita protein supply[a]	kg/person/year	1990-2019: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2019: IPCC (2019)
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized systems	kg N/year	1990-2019: Calculated
Protein	Consumed protein per capita[a]	kg/person/year	1990-2019: Calculated
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2019: IPCC (2019)
$F_{IND-COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the emission factor for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (B1) + *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)* (B2) + *Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)* (B3) = B

where,

Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 (Eq. 6.9),

$$\text{kt } N_2O/\text{year}) = B1$$
$$= [(TN_{DOM\_CENTRAL}) \times (\% \text{ aerobic}_{OTCW})] \times EF_{aerobic} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N$_2$O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N$_2$O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized systems	kg N/year	1990-2019: Calculated
% aerobic$_{OTCW}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2019: Forecasted from the rest of the time series
$EF_{aerobic}$	Emission factor – aerobic systems (0.016)	kg N$_2$O-N/kg N	1990-2019: IPCC (2019)
44/28	Conversion factor	Molecular weight ratio of N$_2$O to N$_2$	Standard conversion
1/10^6	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 (Eq. 6.9), kt

$$N_2O/\text{year}) = B2$$
$$= [(TN_{DOM\_CENTRAL}) \times (\% \text{aerobic}_{CW})] \times EF_{CW} \times 44/28 \times 1/10^6$$

Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.

$$\text{Specific, kt } N_2O/\text{year}) = B3$$
$$= [(POTW\_flow\_CW) \times (N_{CW,INF}) \times 3.785 \times (EF_{CW})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N$_2$O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N$_2$O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment	kg N/year	1990-2019: Calculated
% aerobic$_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992,

Variable	Variable Description	Units	Inventory Years: Source of Value
			1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2019: IPCC (2014)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2019: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2019: IPCC (2014)
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

$$\textit{Emissions from Centrally Treated Anaerobic Systems} \text{ (IPCC 2019 (Eq. 6.9), kt } N_2O/\text{year)} = C$$
$$= [(TN_{DOM\_CENTRAL}) \times (\% \text{ anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment	kg N/year	1990-2019: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004a), respectively

			Data for intervening years obtained by linear interpolation. 2005-2019: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2019: IPCC (2019)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

a Value of this activity data varies over the Inventory time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	Population	Centralized WWT Population (%)	Protein Supply	Protein Consumed
1990	253	75.6	43.1	33.2
2005	300	78.8	44.9	34.7
2015	325	80.1	44.3	34.2
2016	327	81.1	44.7	34.4
2017	329	82.1	44.9	34.6
2018	331	82.0	44.4	34.2
2019	334	82.2	44.4	34.2

Sources: Population - U.S. Census Bureau (2020); WWTP Population - U.S. Census Bureau (2017); Available Protein - USDA (2020b); Protein Consumed - FAO (2020c).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

$$\textit{Emissions from Centrally Treated Systems Discharge} \text{ (U.S. Specific)} = D$$
$$= [(N_{EFFLUENT,IMP} \times EF_{IMP}) + (N_{EFLUENT,NONIMP} \times EF_{NONIMP})] \times 44/28 \times 1/10^6$$

where,

$$\textit{Total organics in centralized treatment effluent} \text{ (IPCC 2019 (Eq. 6.8), kg N/year)} = N_{EFFULENT,DOM}$$
$$= [TN_{DOM\_CENTRAL}[8] \times \% \text{ primary} \times (1\text{-}N_{rem,PRIMARY})] + [TN_{DOM\_CENTRAL} \times \% \text{ secondary} \times (1\text{-}N_{rem,SECONDARY})] +$$
$$[TN_{DOM\_CENTRAL} \times \% \text{ tertiary} \times (1\text{-}N_{rem,TERTIARY})]$$

$$\textit{Total nitrogen in effluent discharged to impaired waterbodies} \text{ (U.S. Specific, kg N/year)} = N_{EFFLUENT,IMP}$$
$$= (N_{EFFULENT,DOM} \times Percent_{IMP})/1000$$

$$\textit{Total nitrogen in effluent discharged to nonimpaired waterbodies} \text{ (U.S. Specific, kg N year)} = N_{EFFLUENT,NONIMP}$$

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[8] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM\_CENTRAL}$.

$$= (N_{EFFLUENT,DOM} \times Percent_{NONIMP})/1000$$

Table 7-35: Variables and Data Sources for N₂O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFLUENT,DOM}$	Total organics in centralized treatment effluent	kg N/year	1990-2019: Calculated
44/28	Conversion factor	Molecular weight ratio of N₂O to N₂	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment	kg N/year	1990-2019: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992.
% secondary	Percent of secondary domestic centralized treatment[a]	%	1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	Data for intervening years obtained by linear interpolation. 2013-2019: Forecasted from the rest of the time series
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2019: IPCC (2019)
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2019: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	EF (discharge to reservoirs/lakes/estuaries) (0.19)	kg N₂O-N/kg N	1990-2019: IPCC (2019)
$EF_{NONIMPr}$	EF (discharge to other waterbodies) (0.005)	kg N₂O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	2010: ERG (2021) 2011: Obtained by linear interpolation 2012: ERG (2021) 2013-2019: Set equal to 2012

[a] Value for this activity data varies over the Inventory time series.

Industrial Wastewater N₂O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater were added to the inventory for the first time and developed according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely

to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the inventory are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021). Wastewater treatment and discharge emissions for these sectors for 2019 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2019, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.3	47.3
Petroleum Refineries	0.2	33.2
Pulp & Paper	0.1	19.0
Breweries	+	0.5
Total	**0.5**	**100**

+ Does not exceed 0.5 kt.
Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi}	= total nitrogen in wastewater for industry *i* for inventory year, kg TN/year.
i	= industrial sector.
P_i	= total industrial product for industrial sector *i* for inventory year, t/year.
W_i	= wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product.
TN_i	= total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3.

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23, and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m³)	Source for Total N
Pulp and Paper	0.22[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

$$N_2O\ Plants_{IND} = \left[\sum_i\left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

$N_2O\ Plants_{IND}$	= N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year.
TN_{INDi}	= total nitrogen in wastewater from industry i for inventory year, kg N/year.
$T_{i,j}$	= degree of utilization of treatment/discharge pathway or system j, for each industry i for inventory year.
i	= industrial sector.
j	= each treatment/discharge pathway or system.
$EF_{i,j}$	= emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. Table 6.8a in the *2019 Refinement* provides 0.016 kg N_2O-N/kg N as a default IPCC value for aerobic treatment systems.
44/28	= conversion of kg N_2O-N into kg N_2O.

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

$$N_2O\ Effluent_{IND} = N_{EFFLUENT,IND} \times EF_{EFFLUENT} \times 44/28$$

where,

$N_2O\ Effluent_{IND}$	= N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)
$N_{EFFLUENT,IND}$	= Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)
$EF_{EFFLUENT}$	= Tier 1 emission factor for wastewater discharged to aquatic environments (kg N_2O-N/kg N)
44/28	= Conversion of kg N_2O-N into kg N_2O.

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N Effluent$_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	8,773,308	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries	1,069,919	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.
Sources: ERG (2021)

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2019 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39 and Table 7-40. For 2019, methane emissions from wastewater treatment were estimated to be between 13.3 and 25.4 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 28 percent below to 38 percent above the 2019 emissions estimate of 18.4 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 16.7 and 81.6 MMT CO_2 Eq., which indicates a range of approximately 37 percent below to 209 percent above the 2019 emissions estimate of 26.4 MMT CO_2 Eq.

For 1990, methane emissions from wastewater treatment were estimated to be between 14.8 and 27.5 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 27 percent below to 37 percent above the 1990 emissions estimate of 20.2 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 12.9 and 60.1 MMT CO_2 Eq., which indicates a range of approximately 31 percent below to 218 percent above the 1990 emissions estimate of 18.7 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2019 Emissions from Wastewater Treatment (MMT CO₂ Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH₄**	**18.4**	**13.3**	**25.4**	**-28%**	**+38%**
Domestic	CH₄	12.1	7.9	17.7	-35%	+47%
Industrial	CH₄	6.4	3.8	10.3	-41%	+62%
Wastewater Treatment	**N₂O**	**26.4**	**16.7**	**81.6**	**-37%**	**+209%**
Domestic	N₂O	25.8	15.7	80.5	-39%	+212%
Industrial	N₂O	0.6	0.6	1.7	-2%	197%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Table 7-40: Approach 2 Quantitative Uncertainty Estimates for 1990 Emissions from Wastewater Treatment (MMT CO₂ Eq. and Percent)

Source	Gas	1990 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH₄**	**20.2**	**14.8**	**27.5**	**-27%**	**+37%**
Domestic	CH₄	14.7	10.1	21.6	-31%	+46%
Industrial	CH₄	5.4	3.3	8.4	-40%	+52%
Wastewater Treatment	**N₂O**	**18.7**	**12.9**	**60.1**	**-31%**	**+221%**
Domestic	N₂O	18.3	12.0	59.3	-34%	+224%
Industrial	N₂O	0.4	0.4	1.3	2%	218%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above and Recalculations section below.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

EPA conducted early engagement and communication with stakeholders on updates prior to the expert review cycle of the current Inventory. EPA held stakeholder meetings in August of 2020 where EPA provided a presentation detailing updates made to both domestic wastewater and a portion of industrial wastewater treatment and requested stakeholder feedback. Stakeholder feedback received is discussed in the Recalculations Discussion and Planned Improvements sections.

Recalculations Discussion

Population data were updated to reflect revised U.S. Census Bureau datasets which resulted in changes to 2010 through 2018 values (U.S. Census Bureau 2020). Protein data were updated to reflect available protein values available for 2014 through 2017 (FAO 2020c). Pulp, paper, and paperboard production data were updated to reflect revised values for 2018 (FAO 2020a). Updated red meat production 2017 and 2018 data, as well as fruits and vegetables processing production 2016 through 2018 data, were based on revised values (USDA 2020a; USDA 2020c).

EPA revised the domestic wastewater CH_4 methodology based on the *2019 Refinement* (IPCC 2019): added a correction factor to account for organics from industrial and commercial contributions to POTWs (1.25); updated the emission factor for centralized aerobic systems which accounts for loss of dissolved methane formed with in the collection system (from 0 to 0.018 kg CH_4/kg BOD); revised the estimate of organics removed with sludge from POTWs; added emission estimates from discharge of domestic wastewater to aquatic environments based on type of receiving water (e.g., reservoir, lake, estuaries); and updated wastewater treatment activity data to align with the updates to organics removed and emissions from discharge to aquatic environments (ERG 2021). All of these changes affected the time series from 1990 through 2018. Domestic wastewater treatment and discharge CH_4 emissions increased an average of 43 percent over the time series, with the smallest increase of 39.6 percent (4.2 MMT CO_2 Eq.) in 1997 and largest increase of 48.0 percent (4.3 MMT CO_2 Eq.) in 2012.

EPA revised the domestic wastewater N_2O methodology based on the *2019 Refinement* (IPCC 2019): added emission estimates from septic systems; added a correction factor to account for nitrogen from household products to POTWs and septic systems (1.17); revised the methodology for treatment plants to account for aerobic and anaerobic treatment systems; updated the emission factor for centralized aerobic systems (from 0 to 0.016 kg N_2O-N/kg N); and revised emission estimates from discharge of domestic wastewater to aquatic environments to account for the condition of the receiving waterbody (i.e., nutrient-impacted/eutrophic conditions, or not impacted) (ERG 2021). All of these changes affected the time series from 1990 through 2018. Domestic wastewater treatment and discharge N_2O emissions increased an average 423 percent over the time series, with the smallest increase of 410 percent (15 MMT CO_2 Eq.) in 2010 and largest increase of 441 percent (14.9 MMT CO_2 Eq.) in 1990.

EPA revised the industrial wastewater CH_4 methodology based on the *2019 Refinement* (IPCC 2019): revised the estimate of organics removed with sludge; added emission estimates from discharge of industrial wastewater to aquatic environments using a Tier 1 methodology and default emission factor; and updated wastewater treatment activity data to align with the updates to emission factor categories (ERG 2021). All of these changes affected the time series from 1990 through 2018. Industrial wastewater treatment and discharge CH_4 emissions increased an average of 7.7 percent over the time series, with the smallest increase of 5.9 percent (0.3 MMT CO_2 Eq.) in 2017 and largest increase of 10.2 percent (0.5 MMT CO_2 Eq.) in 1990.

EPA added industrial wastewater N_2O emissions for the first time based on the *2019 Refinement* (IPCC 2019) methodology. EPA identified four categories with the largest potential contribution to include and added estimates

associated with treatment plant emissions as well as emissions from the discharge of wastewater. These additions affected the entire time series.

The cumulative effect of these recalculations had a large impact on the overall wastewater treatment emission estimates. Over the time series, the average total emissions increased by 118 percent from the previous Inventory. The changes ranged from the smallest increase, 108 percent (20.1 MMT CO_2 Eq.), in 1990, to the largest increase, 135 percent (25.8 MMT CO_2 Eq.), in 2017.

Planned Improvements

EPA implemented revisions based on the *2019 Refinement* but notes the following continued improvements:

- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[9] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge.

- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources.

- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.

- Investigate additional sources for domestic wastewater treatment data.

- Investigate research on methane and nitrous oxide emissions released from domestic treatment processes, as time and resources allow. This would include a 2012 Water Environment Research Foundation study depicting a calculation-based method of potential interest.

- Investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities *as a potential source of updated activity data;*

  - *Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten State Standards). However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.*

- Review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations; and

- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.

- Consider updating the non-consumed protein factor ($F_{NON-CON}$) for centralized treatment to the default value in IPCC (2019). The current U.S.-specific factor is likely overestimating the non-consumed protein as it is based on influent nitrogen (which includes other sources of nitrogen) (i.e., IPCC 2019).

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[9] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

- EPA will continue to look for methods to improve the transparency of the fate of sludge produced in wastewater treatment.

7.3 Composting (CRF Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. If the end product is of lesser quality, it can be disposed of in a landfill.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). This CH_4 is then oxidized to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting because they are considered biogenic, or natural occurring. In accordance with the *2006 IPCC Guidelines*, only anthropogenic emissions are included in the emission estimates for composting.

From 1990 to 2019, the amount of waste composted in the United States increased from 3,810 kt to 22,687 kt. There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,049 kt composted was observed in 2008, which decreased to 18,824 kt composted the following year, presumably driven by the economic crisis of 2009. Between 2009 and 2017, the amount of waste composted gradually increased by approximately 7 percent each year. Emissions of CH_4 and N_2O from composting from 2010 to 2017 have increased by the same percentage. The past two years (2017 and 2018) are similar to 2016 in the amount of material composted and emissions, leading one to conclude that 2017 may be a minor outlier.

In 2019, CH_4 emissions from composting (see Table 7-41 and Table 7-42) were 2.3 MMT CO_2 Eq. (90.7 kt), and N_2O emissions from composting were 2.0 MMT CO_2 Eq. (6.8 kt). Emissions have increased steadily from 2010 and have exhibited a decreasing trend the past two years. The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Volume 4, Chapter 5 (Cropland) of this Inventory, as most agricultural composting operations are assumed to then land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade is attributable primarily to the following factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 22 states representing about 44 percent of the nation's population have enacted such legislation (NERC 2020). There are many more initiatives at the metro and municipal level across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of April 2019, six states (California, Connecticut, New York, Massachusetts, Rhode Island, Vermont) and seven municipalities (Austin, TX; Boulder, CO; Hennepin County, MN; Metro, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, most having taken effect after 2013 (Harvard Law School and CET 2019). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess food for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). There are a growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste, although many states and municipalities currently have limited resources to address this directly.

Estimates for excess food and food waste at a national scale have been limited, but EPA has recently filled this gap. EPA completed a thorough mass balance analysis of all management pathways for food waste and excess food in the *Advancing Sustainable Materials Management: 2018* report (EPA 2020d, commonly referred to as the Facts and Figures reports) using a methodology that expanded the number of management pathways for excess food and food waste to include:

- animal feed;
- bio-based materials/biochemical processing (i.e., rendering);
- codigestion/anaerobic digestion;
- composting/aerobic processes;
- combustion;
- donation;
- land application;
- landfill; and
- sewer/wastewater treatment.

Approximately 18 million tons of food was diverted from landfills in 2018 (EPA 2020d).

Table 7-41: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990	2005	2015	2016	2017	2018	2019
CH_4	0.4	1.9	2.1	2.3	2.4	2.3	2.3
N_2O	0.3	1.7	1.9	2.0	2.2	2.0	2.0
Total	**0.7**	**3.6**	**4.0**	**4.3**	**4.6**	**4.3**	**4.3**

Note: Totals may not sum due to independent rounding.

Table 7-42: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
CH_4	15.2	74.6	84.9	91.1	97.9	90.3	90.7
N_2O	1.1	5.6	6.4	6.8	7.3	6.8	6.8

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process. The methodology assumes all material composted is done so at commercial or industrial composting facilities with windrow piles (widely used because they are cost-effective). Data for small-scale, or household composting or other non-windrow type composting operations are not documented in the national estimates. The methodology assumes the material composted primarily consists of yard trimmings, food waste, and some paper products.

The emissions shown in Table 7-41 and Table 7-42 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

$$E_i = M \times EF_i$$

where,

E_i	= CH_4 or N_2O emissions from composting, kt CH_4 or N_2O,
M	= mass of organic waste composted in kt,
EF_i	= emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006), and
i	= designates either CH_4 or N_2O.

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste. (IPCC 2006). While the moisture content of composting feedstock can vary significantly by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell Composting 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-43 for select years. Estimates of the quantity composted for 1990, 2005, and 2015 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); the estimates of the quantities composted for 2016 and 2017 were taken from EPA's *Advancing Sustainable Materials Management: 2016 and 2017 Tables and Figures* (EPA 2019); the estimate of the quantity composted for 2018 was taken from Table 35 of EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2020); and the estimate for 2019 was extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth between 2018 to 2019, respectively (U.S. Census Bureau 2019). Note that the EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports present quantity of material composted in short tons and the quantities are converted to metric tons to perform the emission calculations under the IPCC framework. The quantity of waste composted in the Facts and Figures reports are developed to provide national coverage, but commercial/industrial composting facilities in Puerto Rico and U.S. territories may not be explicitly included in the mass balance approach used in the reports. This is a planned improvement as noted below.

Table 7-43: U.S. Waste Composted (kt)

Activity	1990	2005	2015	2016	2017	2018	2019
Waste Composted	3,810	18,643	21,219	22,780	24,485	22,580	22,687

Uncertainty and Time-Series Consistency

Uncertainty is the difference between a true value and the measured value. Two uncertainty drivers in the composting emission estimates include the activity data and the emission factors used.

With respect to the activity data used for the composting emission estimates, a true value is fuzzy because data sources presenting facility-specific data are lacking. The methodology applied for the 1990 to 2019 emissions estimates uses annually modeled estimates of waste composted sourced from EPA's Advancing Sustainable Materials Management: Facts and Figures reports. The EPA's Facts and Figures reports uses, at a national level, a modeled materials flow methodology, which relies on a mass balance approach. Models use a number of parameters, which themselves may have varying degrees of uncertainty. No facility-specific or direct state data on commercial composting facilities are used when calculating annual estimates for national quantities of waste composted. EPA collects data from industrial associations, key businesses and industry sources, the Department of Commerce and U.S. Census Bureau. This data is then imported into the materials flow model to estimate tonnage of materials generated, recycled, composted, sent to combustion facilities, beneficially reused, and finally, landfilled. Using estimates from a modeled materials flow approach introduces uncertainty.

The second large area of uncertainty lies with the emission factors themselves. A variety of different organic wastes may be composted at the same facility such as yard waste, animal manure, food waste. One emission factor for methane and nitrous oxide, respectively, are used regardless of the type of waste composted and the composting method. The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Tier 1 methodology.

Emissions from composting in 2019 were estimated to be between 2.1 and 6.4 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the 2019 emission estimate (see Table 7-44).

Table 7-44: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
	CH_4	2.3	1.1	3.4	-50%	+50%
Composting	N_2O	2.0	1.0	3.0	-50%	+50%
	Total	4.3	2.1	6.4	-50%	+50%

The same methodological approaches (e.g., one data source for the quantity of mass composted, the same emission factors) were applied to the entire time series to ensure consistency in emissions from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

The quantity of material composted for 2018 was updated with the publication of the EPA's Advancing Sustainable Materials Management Report (EPA 2020). The quantity of material composted decreased from 24.59 million tons in the previous Inventory report to 22.6 million tons (or 8.19 percent) for 2018 in the current Inventory report. Relatedly, total emissions decreased by 8.19 percent or 0.38 MMT CO_2 Eq. for 2018.

Planned Improvements

In 2017, EPA completed a literature search on emission factors and composting systems and management techniques that will be documented in a technical memorandum for the next (1990 to 2019) Inventory. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the incorporation of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous Inventory cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future Inventory cycles.

Efforts are also being made to improve the completeness of the composting Inventory by incorporating composted waste from U.S. territories. In 2016, EPA conducted a desk-based investigation into industrial/commercial composting facilities in the U.S. territories and identified facilities in Puerto Rico. Three facilities are currently operational, and some operational data and quantities of material composted are available for the past three years. Additional efforts are being made to collect additional historical information to estimate of the quantity of waste composted and/or approximate the population (or households) these facilities serve. This data may be incorporated into the current or future Inventories as a methodological improvement.

7.4 Stand-Alone Anaerobic Digestion (CRF Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and soil amendments (e.g., compost). The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digested sludge. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the IPCC 2006 Guidelines notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a

combination of manure and food waste from restaurants or food processing industry, or a combination of manure and waste from energy crops or crop residues (EPA 2016). The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Stand-alone digesters typically manage food waste from different sources, including food and beverage processing industries. Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters that manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) to produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone AD facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2 (Wastewater Treatment).

From 1990 to 2019, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 866 kt to 10,620 kt, an increase of 92 percent. As described in the Uncertainty and Time-Series Consistency section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates in the early part of the time series are general estimates, extrapolated from data collected later in the time series (i.e., 2015 and later). The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using waste as a renewable energy source.

In 2019, emissions from stand-alone anaerobic digestion facilities were approximately 0.2 MMT CO_2 Eq. (7 kt) (see Table 7-45 and Table 7-46).

Table 7-45: CH₄ Emissions from Stand-Alone Anaerobic Digestion (MMT CO₂ Eq.)

Activity	1990		2005		2015	2016	2017	2018	2019
CH₄ Generation	+		0.1		0.2	0.2	0.2	0.2	0.2
CH₄ Recovered	(+)		(+)		(+)	(+)	(+)	(+)	(+)
CH₄ Emissions	**+**		**0.1**		**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
+ Does not exceed 0.05 MMT CO_2 Eq.

Table 7-46: CH₄ Emissions from Stand-Alone Anaerobic Digestion (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
CH₄ Generation	1		3		8	7	8	8	8
CH₄ Recovered	(+)		(+)		(0.6)	(0.7)	(0.6)	(0.6)	(0.6)
CH₄ Emissions	**1**		**2**		**7**	**7**	**7**	**7**	**7**

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.
+ Does not exceed 0.5 kt.

Methodology

Methane from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the digestion process.

The emissions presented in Table 7-45 were estimated largely using the IPCC default (Tier 1) methodology given in Equation 4.1 below (Volume 5, Chapter 4, IPCC 2006), which is the product of an emission factor and the mass of organic waste processed. Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later).

$$CH_4 \; Emissions = \sum_i (M_i \times EF_i) \times 10^{-3} - R$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4

M_i = mass of organic waste treated by biological treatment type i, Gg, see Table 7-29

EF = emission factor for treatment i, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4

i = anaerobic digestion

R = total amount of CH_4 recovered in inventory year, Gg CH_4

= Biogas x 0.0283 x minutes/year x biogas CH_4 density x C_{CH4} x 1/10^9 x (1-DE)

Where,

Biogas = the annual amount of biogas produced, standard cubic feet per minute (scfm)

0.0283 = conversion factor cubic meter/cubic feet

525,600 = minutes per year

662 = CH_4 density in biogas (EPA 1993), g CH_4/m^3 CH_4

65% = C_{CH4}, concentration of CH_4 in the biogas

1/10^9 = conversion factor, grams to kt

0.99 = destruction efficiency for combustion unit

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor recommended by the IPCC 2006 Guidelines (0.8 Mg/Gg CH_4) is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from recent EPA surveys of anaerobic digestion facilities (US EPA 2018 and 2019). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Two reports with survey results have been published to date (the third is expected in late 2021):

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (US EPA, 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (US EPA, 2019).

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (US EPA 2019).

The annual quantity of waste digested for 1990 to 2014 (only 1990 and 2005 are shown) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 and 2016 collected through EPA's survey data (EPA 2018; EPA 2019). Masked survey responses of food and non-food waste processed were shared with the Inventory team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the 1990 to 2019 inventory is calculated as follows:

$$Weighted\ Average\ Waste\ Processed = \frac{(W_{2016} \times Fac_{2016} + W_{2015} \times Fac_{2015})}{(Fac_{2016} + Fac_{2015})}$$

where:

> W = total waste processed in the respective survey year, food and non-food waste (short tons).

> Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA 2018 and 2019.

Estimates of the quantity of waste digested (M, wet weight as generated) are presented in Table 7-47 for select years and the number of facilities that reported annual quantities of waste digested to the EPA survey were 45 and 44 in 2015 and 2016, respectively (masked facility data provided by the EPA AD survey data collection team).

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from 2015 and 2016 survey data (216,494 short tons) by the count of operating facilities in each year. This calculation assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future inventories as described in the Planned Improvements section. Estimates of the quantity digested for 2015 and 2016 were taken from EPA's AD survey data (EPA 2018; EPA 2019, respectively). The estimate of waste digested for 2017 to 2019 were extrapolated using the average of the waste digested from the 2015 and 2016 surveys as a proxy. Planned updates to the waste digested for 2017 to 2019 are described in the Planned Improvements section.

Table 7-47: U.S. Waste Digested (kt)

Activity	1990		2005		2015	2016	2017	2018	2019
Waste Digested[1]	786		3,142		9,963	9,305	9,634	9,634	9,634

[1] The amount of waste digested primarily consists of food waste. The amount processed for all years is likely an underestimate because the estimates were developed from survey data provided by operating facilities for 2015 and 2016 (EPA 2018; EPA 2019). Facilities that did not respond to the EPA surveys are not included and all years except 2015 and 2016 are estimated using assumptions regarding the number of operating facilities and the weighted average of waste digested. Additionally, the liquid portion of the waste digested in 2015 and 2016 are not included due to limited information on the specific waste types to perform the unit conversion to kt. The average waste digested as reported in EPA 2018 and 2019 is used as a proxy for years 2017 to 2019.

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA 2019. This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series. This is likely an

overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions, while the directly reported annual amount of waste processed from the survey data are used for 2015 to 2017.

Table 7-48: Estimated Number of Stand-Alone AD Facilities Operating from 1990-2019[1]

Year	1990		2005		2015	2016	2017	2018	2019
Estimated Count of Operational Facilities	4		16		56	58	58	60	60

[1] The count of operational facilities was visually estimated from Figure 5 in EPA 2020, which presents the count of the first year of digester operation. The number of operational facilities by year is assumed to be the cumulative total from the prior year. This method assumes all facilities are operating from 1990, or their first year of operation, to 2019. This is further discussed in the Uncertainty and Time Series section.

Activity data for the amount of biogas recovered (R in the emission calculation equation) is limited across the time series. Currently, there are only two data points (2015 and 2016) represented for the entire sector, as reported in the EPA AD Data Collection Survey reports (EPA 2018 and 2019). The total quantity of collected biogas from the survey respondents for 2015 and 2016 is reported in standard cubic feet per minute (scfm) as shown in Table 7-49. Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that only emissions from flaring can be reported under the waste sector. The top three known uses of the biogas generation for stand-alone digesters are for combined heat and power (CHP), the production of electricity that is sold to the grid, and using the biogas to fuel boilers and furnaces to heat the digestor and other facility spaces (EPA 2018; EPA 2019). Thus, no biogas is assumed to be flared.

Table 7-49: Estimated Biogas Produced and Methane Recovered from Stand-Alone AD Facilities Operating from 1990-2019[1]

Activity	1990		2005		2015	2016	2017	2018	2019
Total Biogas Produced (scfm)[2]	820		3,279		9,176	10,498	11,886	12,296	12,296
R, recovered CH_4 from biogas (kt)[3]	0.05		0.21		0.59	0.67	0.63	0.63	0.63

[1] Total biogas produced in standard cubic feet per minute (scfm) was reported in aggregate in the EPA survey data (EPA 2018 and 2019) for 2015 and 2016. The quantities presented in this table are likely underestimates because not all operational facilities provided a survey response to the EPA AD Data Collection Surveys.

[2] Data for all years in the time series except for 2015 and 2016 are extrapolated using the average of the total biogas collected in 2015 and 2016, divided by the average number of survey responses to generate an average estimate of biogas collected per facility, which is then multiplied by the total facility count (as shown in Table 7-30).

[3] The quantity of CH_4 recovered from the biogas produced is estimated for all years except 2015 and 2016, which are taken from EPA (2018) and (2019).

Uncertainty and Time-Series Consistency

The methodology applied for the 1990 to 2019 emissions estimates should be considered a starting point to build on in future years. Two years of facility-provided data are available (2015 and 2016) while the rest of the time series is estimated based off an assumption of facility counts and a weighted average annual waste processed developed from the two years of survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD survey (EPA 2018; EPA 2019) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, annual waste processed, and biogas recovered. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.

2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed is not included in the estimated quantity of annual waste digested because data on the waste types are not available to convert the quantity from gallons to tons. This slightly underestimates the quantity of waste digested and CH_4 emissions.

3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e., facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Tier 1 methodology.

Emissions from stand alone anaerobic digesters in 2019 were estimated to be between 0.1 and 0.3 MMT CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the 2019 emission estimate of each gas (see Table 7-50).

Table 7-50: Tier 1 Quantitative Uncertainty Estimates for Emissions from Digestion (MMT CO_2 Eq. and Percent)

Source	Gas	2019 Emission Estimate (MMT CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate			
			(MMT CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stand-alone Anaerobic Digestion	CH₄	0.2	0.1	0.3	-50%	+50%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

This is a new source category included for the current (1990 to 2019) Inventory; thus, no recalculations have been made.

Planned Improvements

Several potential improvements will be investigated for inclusion in future inventory years with the intent of reducing the uncertainties described in the Uncertainty and Time-Series Consistency section. First, EPA plans to incorporate survey data from future EPA AD Data Collection Surveys when the survey data are published. The next report for 2017 is expected to be published in 2021. This addition will change the estimated emissions for 2017 and potentially the weighted average applied to the 1990 to 2014 time series. EPA will pull in survey data for future years when published. This revision will change emissions estimates for 2018 and 2019.

Second, EPA will re-assess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed. The initial methodology described here assumes the same amount of waste is processed each year from 2017 to 2019.

Third, EPA will conduct additional research to confirm the number of operational facilities by year prior to 2015 and how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

Fourth, EPA will investigate the amount of recovered biogas for years prior to 2015 (i.e., the years prior to the EPA AD Data Collection Surveys). Currently, only two years of data of recovered biogas are available and the primary purpose will be to understand whether the range of recovered biogas from the 2015 and 2016 survey data are reflective of earlier years.

Fifth, the uncertainty assessment will be further reviewed to confirm the appropriateness of the uncertainty factor(s) to be applied.

7.5 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2019 resulted in 11.8 MMT CO_2 Eq. of emissions, over half of which (6.6 MMT CO_2 Eq.) is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided. An analysis of the likely level of emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

7.6 Waste Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursor gases. The reporting requirements of the UNFCCC[10] request that information be provided on precursor greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-CH_4 volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse

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[10] See <http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>.

gases. Total emissions of NO$_x$, CO, and NMVOCs from waste sources for the years 1990 through 2019 are provided in Table 7-51. Sulfur dioxide emissions are presented in Section 2.3 of the Trends chapter and Annex 6.3.

Table 7-51: Emissions of NO$_x$, CO, and NMVOC from Waste (kt)

Gas/Source	1990	2005	2015	2016	2017	2018	2019
NO$_x$	+	2	2	1	1	1	1
Landfills	+	2	2	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0
CO	1	7	7	6	5	5	5
Landfills	1	6	7	6	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	0	0	0	0	0	0
NMVOCs	673	114	63	57	52	52	52
Wastewater Treatment	57	49	27	25	22	22	22
Miscellaneous[a]	557	43	24	22	20	20	20
Landfills	58	22	12	11	10	10	10

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.5 kt.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Methodology

Emission estimates for 1990 through 2019 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2020) and disaggregated based on EPA (2003). Emission estimates of these gases were provided by sector, using a "top down" estimating procedure—emissions were calculated either for individual sources or for many sources combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Uncertainty and Time-Series Consistency

No quantitative estimates of uncertainty were calculated for this source category. Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. Details on the emission trends through time are described in more detail in the Methodology section, above.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) "Other" sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, as efforts are made to improve the estimates through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."

In general, when methodological changes have been implemented, the previous Inventory's time series (i.e., 1990 to 2018) will be recalculated to reflect the change, per guidance in IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies, and do not necessarily impact the entire time series.

The results of all methodological changes and historical data updates made in the current Inventory are presented in Figure 9-1, Table 9-1, and Table 9-2. Figure 9-1 presents the impact of recalculations by sector and on net total emissions across the timeseries. Table 9-1 summarizes the quantitative effect of all changes on U.S. greenhouse gas emissions by gas across the Energy, Industrial Processes and Product Use (IPPU), Agriculture, and Waste sectors, while Table 9-2 summarizes the quantitative effect of changes on annual net fluxes from Land Use, Land-Use Change, and Forestry (LULUCF). Both the figure and tables present results relative to the previously published Inventory (i.e., the 1990 to 2018 report) in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.). To understand the details of any specific recalculation or methodological improvement, see the *Recalculations* within each source/sink categories' section found in Chapters 3 through 7 of this report. A discussion of Inventory improvements in response to review processes is described in Annex 8.

The Inventory includes new categories not included in the previous Inventory that improve completeness of the national estimates. Specifically, the current report includes methane emissions from anaerobic digestion at biogas facilities, N_2O emissions from industrial wastewater, CF_4 emissions from Low Voltage Anode Effect (LVAE) during aluminum production and change in carbon stocks for belowground biomass in managed coastal wetlands.

The following source and sink categories underwent the most significant methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

- *Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks (CO_2).* The methods used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes and harvested wood products (HWPs) from 1990 through 2019 are consistent with those used in the 1990 through 2018 Inventory. However, population estimates of carbon stocks and stock changes were compiled using NFI data from each U.S. state and national estimates were compiled by summing over all states. In past Inventories, population estimates were compiled by four geographic regions and summed over all regions to compile national estimates. Also, the state-level disaggregation contributed to

identifying an error in the compilation of the Alaska time series data resulting in a 1-year misalignment in carbon stock changes for this state in comparison to the 1990 through 2018 Inventory. This error has been corrected resulting in differences in each year of the time series (i.e., 1990 to 2018), given the one-year misalignment, with substantial differences in major fire years in Alaska. Soil carbon stocks decreased in the latest Inventory relative to the previous Inventory and this change can be attributed to refinements in the Digital General Soil Map of the United States (STATSGO2) dataset where soil orders may have changed in the updated data product. These changes resulted in an average annual increase in C stock change losses of 42.7 MMT CO_2 Eq. (6.5 percent), across the 1990 through 2018 time series, relative to the previous Inventory.

- *Wastewater Treatment (N_2O).* EPA revised the domestic wastewater N_2O methodology based on the *2019 Refinement* (IPCC 2019): added emission estimates from septic systems; added a correction factor to account for nitrogen from household products to POTWs and septic systems (1.17); revised the methodology for treatment plants to account for aerobic and anaerobic treatment systems; updated the emission factor for centralized aerobic systems (from 0 to 0.016 kg N_2O-N/kg N); and revised emission estimates from discharge of domestic wastewater to aquatic environments to account for the condition of the receiving waterbody (i.e., nutrient-impacted/eutrophic conditions, or not impacted) (ERG 2020). EPA added industrial wastewater N_2O emissions for the first time based on the *2019 Refinement* (IPCC 2019) methodology. These additions are on average 2 percent of wastewater N_2O emissions across the entire time series. The changes to domestic and industrial wastewater affected the time series from 1990 through 2018. Nitrous oxide emissions from wastewater increased an average 435 percent over the time series, with the smallest increase of 15.3 MMT CO_2 Eq. (453 percent) in 1990 and largest increase of 21.4 MMT CO_2 Eq. (412 percent) in 2017.

- *Land Converted to Forest Land: Changes in Carbon Stocks (CO_2).* The Land Converted to Forest Land estimates in this Inventory are based on the land use change information in the annual National Forest Inventory (NFI). All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass C stocks removed from Croplands and Grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil C stock changes (Ogle et al. 2003, 2006; IPCC 2006). The incorporation of the most recent annual NFI data into the compilation system resulted in a decrease in C stock changes. Overall, the Land Converted to Forest Land C stock changes decreased by an average of 10.4 percent (11.5 MMT CO_2 Eq.) over the time series.

- *Non-Energy Use of Fuels (CO_2).* Adjustments were made to activity data, carbon content coefficients, and heat contents for hydrocarbon gas liquids (HGL) for 1990 to 2018. In previous Inventories, HGL activity data from 1990 to 2007 were extracted from the American Petroleum Institute's Sales of Natural Gas Liquids and Liquefied Refinery Gases. Historical HGL activity data from 1990 to 2007 were adjusted to use EIA's Petroleum Supply Annual tables for consistency with the rest of the time series (i.e., 2008 to 2019). In addition, the HGL carbon content coefficient for NEU was updated by separating each fuel out by its natural gas liquid (NGL) and associated olefin to calculate a more accurate and annually variable factor, and the heat contents for HGL and pentanes plus were updated using updated data from EIA's Monthly Energy Review (EIA 2020). Non-energy use of petroleum coke consumption was adjusted to account for leap years when converting from barrels per day to barrels per year. The "miscellaneous products" category reported by EIA includes miscellaneous products that are not reported elsewhere in the EIA data set. The miscellaneous products category reported by EIA was assumed to be mostly petroleum refinery sulfur compounds that do not contain carbon (EIA 2019). Therefore, the carbon content for miscellaneous products was updated to be zero across the time series. Overall, these changes resulted in an average annual decrease of 10.9 MMT CO_2 Eq. (8.7 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2018, relative to the previous Inventory. This decrease is primarily due to the removal of miscellaneous products, which previously constituted an average of 8.2 percent of total emissions from 1990 to 2018.

- *Natural Gas Systems (CH_4).* EPA received information and data related to the Inventory emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder

feedback on updates under consideration, and new studies. EPA thoroughly evaluated relevant information available and made several updates to the Inventory, including using revised emission factors and produced water volumes to calculate produced water emissions (production segment), and using GTI (2019) along with GTI 2009 study data to calculate customer meter emissions (distribution segment). In addition, certain sources did not undergo methodological updates, but CH_4 estimates changed due to GHGRP data submission revisions and revisions to other input activity data sets. Overall, the changes resulted in an average annual increase of 6.6 MMT CO_2 Eq. (4.2 percent) in methane emissions from natural gas systems over the time series.

- *Fossil Fuel Combustion (CO_2).* The EIA (2020c) updated energy consumption statistics across the time series relative to the previous Inventory. As a result of revised natural gas heat contents, EIA updated natural gas consumption in the residential, commercial, and industrial sectors for 2018. Approximate heat rates for electricity and the heat content of electricity were revised for natural gas and noncombustible renewable energy, which impacted electric power energy consumption by sector. EIA also revised sector allocations for distillate fuel oil, residual fuel oil, and kerosene for 2018, and for propane for 2010 through 2012, 2014, 2017, and 2018, which impacted LPG by sector. EIA revised product supplied totals for crude oil and petroleum products, which impacted the nonfuel sequestration statistics, particularly for lubricants for 2018 and LPG for 2010 through 2018 relative to the previous Inventory. These changes resulted in an average annual decrease 6.4 MMT CO_2 Eq. (0.1 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2018, relative to the previous Inventory.

- *Wastewater Treatment (CH_4).* EPA revised the domestic wastewater CH_4 methodology based on the *2019 Refinement* (IPCC 2019): added a correction factor to account for organics from industrial and commercial contributions to publicly owned treatment works (POTWs) (1.25); updated the emission factor for centralized aerobic systems which accounts for loss of dissolved methane formed with in the collection system (from 0 to 0.018 kg CH_4/kg BOD); revised the estimate of organics removed with sludge from POTWs; added emission estimates from discharge of domestic wastewater to aquatic environments based on type of receiving water (e.g., reservoir, lake, estuaries); and updated wastewater treatment activity data to align with the updates to organics removed and emissions from discharge to aquatic environments (ERG 2020). Domestic wastewater treatment and discharge CH_4 emissions increased an average of 43 percent over the time series. The industrial wastewater CH_4 methodology was also revised based on the based on the *2019 Refinement* (IPCC 2019) as described in Chapter 7, and contributed to smaller recalculation impacts, i.e., averaging a 7.7 percent increase over the time series. The changes to domestic and industrial wastewater affected the time series from 1990 through 2018. These changes resulted in an average annual increase of 4.6 MMT CO_2 Eq. (30.1 percent) in methane emissions from wastewater treatment across the time series.

- *Gasoline and Diesel Fuel Fossil Fuel Combustion (CO_2).* EPA revised distillate fuel oil and motor gasoline carbon contents, which impacted petroleum emissions in the transportation, residential, commercial, and industrial sectors. The combined effect of both the diesel fuel and gasoline emission factor update was an increase in emissions early in the time series and then decreases in emissions in more recent years. For years 1990 through 2005, the average annual increase in total emissions was about 7 MMT CO_2 (0.1 percent of emissions). For the years 2006 to 2018 the average annual decrease in total emissions is about 5 MMT CO_2 (less than 0.1 percent of emissions).

- *Mobile Combustion (CH_4).* Updates were made to CH_4 and N_2O emission factors for newer non-road gasoline and diesel vehicles. Previously, these emission factors were calculated using the updated IPCC (2006) Tier 3 guidance and the nonroad component of EPA's MOVES2014b model. Methane emission factors were calculated directly from MOVES. Updated emission factors were developed this year using EPA engine certification data for non-road small and large spark-ignition (SI) gasoline engines and compression-ignition diesel engines (2011 and newer), as well as non-road motorcycles (2006 and newer), SI marine engines (2011 and newer), and diesel marine engines (2000 and newer). The result of these changes was a net decrease in CH_4 emissions from mobile combustion relative to the previous Inventory.

Methane emissions from mobile combustion decreased by an average of 4.5 MMT CO_2 Eq. (47.5 percent) throughout the time series.

- *Mobile Combustion (N_2O).* Updates were made to CH_4 and N_2O emission factors for newer non-road gasoline and diesel vehicles. Previously, these emission factors were calculated using the updated IPCC (2006) Tier 3 guidance and the nonroad component of EPA's MOVES2014b model. Nitrous oxide emission factors are calculated using MOVES-Nonroad activity and emission factors in g/kWh by fuel type from the European Environment Agency. Updated emission factors were developed this year using EPA engine certification data for non-road small and large spark-ignition (SI) gasoline engines and compression-ignition diesel engines (2011 and newer), as well as non-road motorcycles (2006 and newer), SI marine engines (2011 and newer), and diesel marine engines (2000 and newer). The result of these changes was an increase in N_2O emissions from mobile combustion relative to the previous Inventory. Nitrous oxide emissions from mobile combustion increased by an average of 3.5 MMT CO_2 Eq. (11.3 percent) throughout the time series.

Figure 9-1: Impacts from Recalculations to U.S. Greenhouse Gas Emissions by Sector
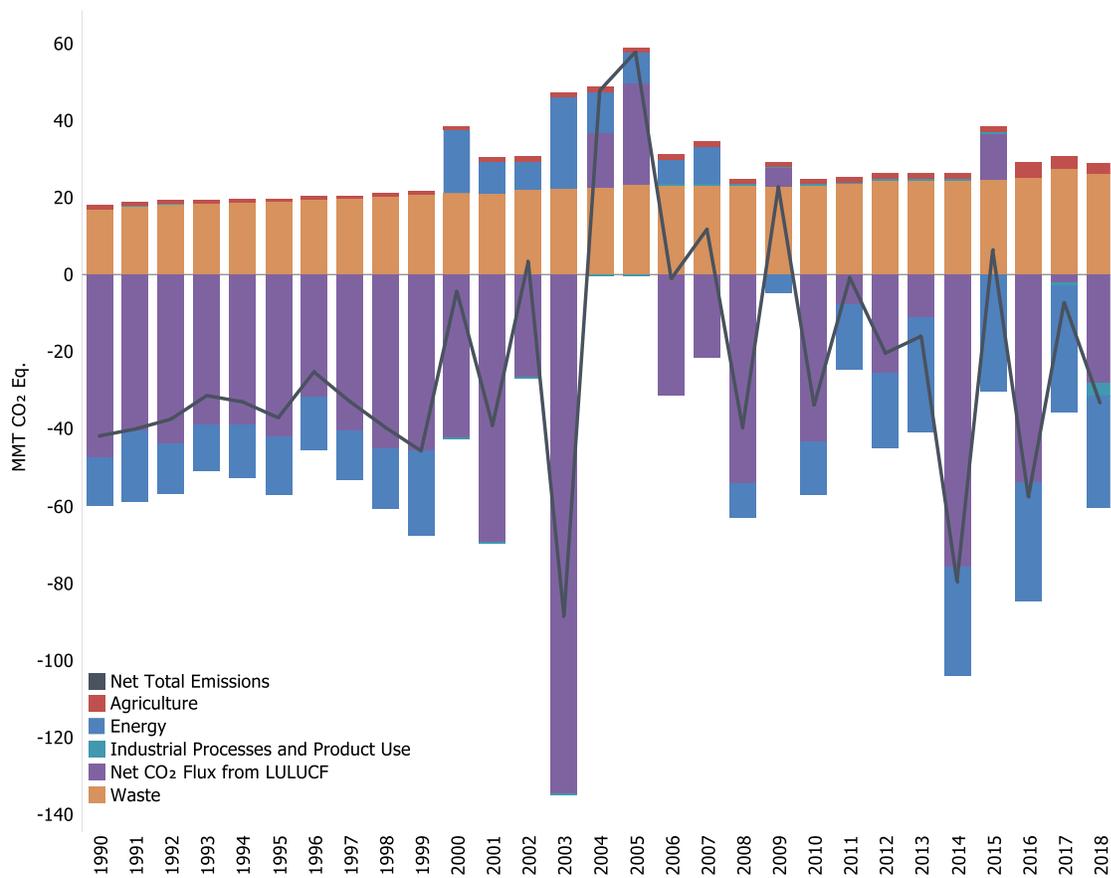
Table 9-1: Revisions to U.S. Greenhouse Gas Emissions (MMT CO$_2$ Eq.)

Gas/Source	1990	2005	2015	2016	2017	2018	Average Annual Change
CO$_2$	**(14.8)**	**2.6**	**(40.7)**	**(44.2)**	**(45.9)**	**(49.4)**	**(17.0)**
Fossil Fuel Combustion	(8.5)	12.8	(23.5)	(30.9)	(37.8)	(40.4)	(6.4)
Electric Power Sector	NC	0.1	+	+	+	0.1	+
Transportation	+	2.5	(6.0)	(5.4)	(4.8)	(4.1)	1.4
Industrial	(3.2)	2.8	(4.0)	(8.9)	(14.9)	(19.6)	(1.9)
Residential	0.4	1.0	(0.5)	(0.4)	(0.4)	0.8	0.3
Commercial	0.1	0.3	(0.8)	(0.8)	(0.8)	(0.8)	(0.1)
U.S. Territories	(5.8)	6.2	(12.1)	(15.4)	(16.8)	(16.8)	(6.1)
Non-Energy Use of Fuels	(6.8)	(10.6)	(18.6)	(13.8)	(9.6)	(4.8)	(10.9)
Natural Gas Systems	(0.1)	(0.1)	(0.2)	0.2	0.8	(1.1)	(0.1)
Cement Production	NC	NC	NC	NC	NC	(1.4)	+
Lime Production	NC	NC	NC	+	+	(0.1)	+
Other Process Uses of Carbonates	NC	NC	NC	0.5	+	(2.5)	(0.1)
Glass Production	NC	NC	NC	+	+	+	+
Soda Ash Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	0.5	0.2	0.1	(0.3)	+
Incineration of Waste	0.1	0.2	0.8	0.6	0.4	0.4	0.3
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	+	NC	NC	NC	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	+	+	(0.6)	(2.1)	(1.4)	(0.1)
Urea Consumption for Non-Agricultural Purposes	NC	NC	NC	NC	1.3	2.2	0.1
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC	NC
Petrochemical Production	NC	NC	NC	NC	NC	(0.1)	+
Carbide Production and Consumption	+	+	+	+	+	+	+
Lead Production	NC	NC	NC	NC	NC	NC	NC
Zinc Production	NC	NC	+	(0.1)	(0.1)	+	+
Petroleum Systems	0.1	(0.1)	(0.2)	(1.1)	0.5	0.3	(0.1)
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	NC	NC	NC	NC
Liming	NC	NC	NC	NC	NC	(0.9)	+
Urea Fertilization	0.4	0.4	0.6	0.8	0.5	0.6	0.5
International Bunker Fuels[a]	NC	0.1	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[b]	NC	NC	NC	(0.6)	(9.9)	(9.3)	(0.7)
CH$_4$[c]	**2.5**	**6.6**	**13.1**	**18.1**	**18.1**	**21.5**	**7.8**
Stationary Combustion	+	+	+	(0.1)	(0.2)	(0.1)	+
Mobile Combustion	(6.5)	(5.6)	(1.0)	(0.9)	(0.8)	(0.7)	(4.5)
Coal Mining	NC	+	+	+	+	+	+
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	NC	NC
Natural Gas Systems	3.6	6.1	8.0	11.5	9.5	12.6	6.6
Petroleum Systems	2.8	0.6	0.9	0.2	0.7	1.1	1.1
Abandoned Oil and Gas Wells	0.2	0.2	0.2	0.2	0.1	0.2	0.2
Petrochemical Production	NC	NC	NC	NC	NC	NC	NC
Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC

Enteric Fermentation	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Manure Management	NC	NC	NC	NC	NC	NC	NC
Rice Cultivation	NC	NC	NC	2.3	2.1	2.2	0.2
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Landfills	(3.0)	0.1	0.1	+	1.7	1.5	(0.9)
Wastewater Treatment	4.8	4.6	4.3	4.3	4.3	4.2	4.6
Composting	NC	NC	NC	NC	NC	(0.2)	+
Anaerobic Digestion at Biogas Facilities	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
International Bunker Fuels[a]	NC	NC	NC	NC	NC	NC	NC
N$_2$O[c]	**18.0**	**23.2**	**24.4**	**24.7**	**25.0**	**24.7**	**22.2**
Stationary Combustion	+	+	+	+	(0.2)	(0.2)	+
Mobile Combustion	2.7	4.2	3.4	3.4	3.6	3.6	3.5
Adipic Acid Production	+	NC	NC	NC	NC	NC	+
Nitric Acid Production	NC	NC	NC	NC	NC	0.2	+
Manure Management	NC	NC	NC	NC	NC	NC	NC
Agricultural Soil Management	+	0.3	0.4	0.3	0.2	0.1	0.2
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	15.3	18.6	20.6	21.0	21.4	21.1	18.5
N$_2$O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	(0.2)	+
Electronics Industry	NC	NC	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
Petroleum Systems	+	+	+	+	+	+	+
International Bunker Fuels[a]	NC	NC	NC	NC	NC	NC	NC
HFCs, PFCs, SF$_6$ and NF$_3$	**+**	**(1.1)**	**(2.1)**	**(2.4)**	**(2.2)**	**(2.0)**	**(0.9)**
HFCs	**NC**	**(1.1)**	**(2.2)**	**(2.4)**	**(2.2)**	**(1.8)**	**(1.0)**
Substitution of Ozone Depleting Substances[d]	NC	(1.1)	(2.2)	(2.4)	(2.2)	(1.8)	(1.0)
HCFC-22 Production	NC	NC	NC	NC	NC	NC	NC
Electronics Industry	NC	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	NC	+	+	+
PFCs	**NC**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aluminum Production	NC	NC	0.1	0.1	0.1	0.1	0.1
Electronics Industry	NC	+	+	+	+	+	+
Substitution of Ozone Depleting Substances[d]	NC	NC	NC	NC	NC	NC	NC
SF$_6$	**NC**	**+**	**+**	**+**	**+**	**(0.2)**	**+**
Electrical Transmission and Distribution	NC	NC	+	+	+	(0.2)	+
Electronics Industry	NC	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	NC	(0.1)	(0.1)	+
NF$_3$	**NC**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	NC	+	+	+	+	+	+
Unspecified Mix of HFCs, NF$_3$, PFCs and SF$_6$	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+
Net Emissions (Sources and Sinks)	**(41.8)**	**57.9**	**6.4**	**(57.6)**	**(7.1)**	**(33.1)**	**19.8**
Percent Change	**-0.7%**	**0.9%**	**0.1%**	**-1.0%**	**-0.1%**	**-0.6%**	**-0.4%**

Notes: Net change in total emissions presented without LULUCF. Totals may not sum due to independent rounding.

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq. or 0.05 percent.

* Indicates a new source for the current Inventory year. Emissions from new sources are captured in net emissions and percent change totals.

[a] Emissions from International Bunker Fuels are not included in totals.

[b] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.
[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals in Table 9-2. L LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and Coastal Wetlands Remaining Coastal Wetlands; CH_4 emissions from Land Converted to Coastal Wetlands; and N_2O emissions from Forest Soils and Settlement Soils.[d] Small amounts of PFC emissions also result from this source.

Table 9-2: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO$_2$ Eq.)

Land-Use Category	1990	2005	2015	2016	2017	2018	Average Annual Change
Forest Land Remaining Forest Land	**(53.7)**	**17.1**	**4.8**	**(64.0)**	**(12.5)**	**(38.5)**	**(42.8)**
Changes in Forest Carbon Stocks[a]	(53.7)	17.1	4.7	(64.0)	(12.0)	(35.4)	(42.7)
Non-CO$_2$ Emissions from Forest Fires[b]	+	+	+	+	(0.5)	(3.1)	(0.1)
N$_2$O Emissions from Forest Soils[c]	NC	NC	NC	NC	NC	NC	NC
Non-CO$_2$ Emissions from Drained Organic Soils[d]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Forest Land	**11.3**	**11.5**	**11.6**	**11.6**	**11.5**	**11.5**	**11.5**
Changes in Forest Carbon Stocks[e]	11.3	11.5	11.6	11.6	11.5	11.5	11.5
Cropland Remaining Cropland	**NC**	**NC**	**NC**	**+**	**+**	**+**	**+**
Changes in Mineral and Organic Soil Carbon Stocks	NC	NC	NC	+	+	+	+
Land Converted to Cropland	**(2.3)**	**(1.7)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.7)**
Changes in all Ecosystem Carbon Stocks[f]	(2.3)	(1.7)	(1.1)	(1.1)	(1.1)	(1.1)	(1.7)
Grassland Remaining Grassland	**(0.8)**	**(0.7)**	**(0.5)**	**0.2**	**0.4**	**0.5**	**(0.6)**
Changes in Mineral and Organic Soil Carbon Stocks	(0.8)	(0.7)	(0.5)	0.2	0.4	0.5	(0.6)
Non-CO$_2$ Emissions from Grassland Fires[g]	NC	NC	+	+	+	+	+
Land Converted to Grassland	**0.4**	**0.2**	**(0.8)**	**0.7**	**0.5**	**0.5**	**0.2**
Changes in all Ecosystem Carbon Stocks[f]	0.4	0.2	(0.8)	0.7	0.5	0.5	0.2
Wetlands Remaining Wetlands	**(3.0)**	**(0.6)**	**(3.4)**	**(3.4)**	**(3.3)**	**(3.3)**	**(1.3)**
Changes in Organic Soil Carbon Stocks in Peatlands	NC	NC	NC	NC	0.1	0.1	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(3.4)	(0.9)	(3.7)	(3.7)	(3.7)	(3.6)	(1.6)
CH$_4$ Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.3
N$_2$O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	+	+	+	+	+
Non-CO$_2$ Emissions from Peatlands Remaining Peatlands	NC	NC	NC	NC	+	+	+
Land Converted to Wetlands	**0.7**	**0.7**	**0.2**	**0.2**	**0.2**	**0.2**	**0.6**
Changes in Biomass, DOM, and Soil Carbon Stocks	0.5	0.5	+	+	+	+	0.4
CH$_4$ Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**NC**	**NC**	**0.9**	**1.9**	**2.2**	**2.3**	**0.3**
Changes in Organic Soil Carbon Stocks	NC	NC	NC	+	+	+	+
Changes in Settlement Tree Carbon Stocks	NC	NC	NC	NC	NC	NC	NC
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	NC	NC	0.9	1.9	2.2	2.3	0.3

N₂O Emissions from Settlement Soils[h]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Settlements	**NC**	**NC**	**NC**	+	+	+	+
Changes in all Ecosystem Carbon Stocks[f]	NC	NC	NC	+	+	+	+
LULUCF Total Net Flux[i]	**(48.0)**	**26.1**	**11.2**	**(54.3)**	**(2.0)**	**(25.3)**	**(34.3)**
LULUCF Emissions[j]	**0.6**	**0.5**	**0.5**	**0.4**	**(0.1)**	**(2.7)**	**0.4**
LULUCF Sector Total[k]	**(47.4)**	**26.6**	**11.7**	**(53.9)**	**(2.1)**	**(27.9)**	**(33.9)**
Percent Change	**-5.6%**	**3.3%**	**1.5%**	**-6.8%**	**-0.3%**	**-3.6%**	**-4.3%**

Note: Totals may not sum due to independent rounding.

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO₂ Eq. or 0.05 percent.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include CH₄ and N₂O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include N₂O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH₄ and N₂O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[g] Estimates include CH₄ and N₂O emissions from fires on both *Grassland Remaining Grassland* and *Land Converted to Grassland.*

[h] Estimates include N₂O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements* because it is not possible to separate the activity data at this time.

[i] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH₄ and N₂O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and Coastal Wetlands Remaining Coastal Wetlands; CH₄ emissions from Land Converted to Coastal Wetlands; and N₂O emissions from Forest Soils and Settlement Soils.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH₄ and N₂O emissions to the atmosphere plus net carbon stock changes.

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