

Inventory of U.S. Greenhouse Gas Emissions and Sinks:

1990 – 2014

APRIL 15, 2016

U.S. Environmental Protection Agency
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For more information regarding climate change and greenhouse gas emissions, see the EPA web site at <<http://www3.epa.gov/climatechange>>.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to comply with existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Under decision 3/CP.5 of the UNFCCC Conference of the 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, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document is announced via Federal Register Notice and is posted on the EPA web site. Copies are also mailed upon request. The public comment period is generally limited to 30 days; however, comments received after the closure of the public comment period are accepted and considered for the next edition of this annual report.

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Executive Summary

An emissions inventory that identifies and quantifies a country's primary anthropogenic¹ 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 sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent mechanism 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

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...”³ The United States views this report as an opportunity to fulfill these commitments.

This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2014. To ensure that the U.S. emissions inventory is comparable to those of other UNFCCC Parties, the estimates presented here were calculated using methodologies consistent with those recommended in the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The structure of this report is consistent with the UNFCCC guidelines for inventory reporting.⁴

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the gross emissions total presented in this report for the United States excludes emissions and sinks from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from LULUCF. All emissions and sinks are calculated using internationally-accepted methods provided by the

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). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <<http://unfccc.int>>.

⁴ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

IPCC.⁵ Additionally, the calculated emissions and sinks 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.⁶ The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP). 40 CFR part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO₂) underground for sequestration or other reasons.⁷ Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective methodological and planned improvements sections in this report's chapters, EPA is using the data, as applicable, to improve the national estimates presented in this Inventory.

ES.1. Background Information

Greenhouse gases trap heat and make the planet warmer. The most important greenhouse gases directly emitted by humans include CO₂, methane (CH₄), nitrous oxide (N₂O), and several other fluorine-containing halogenated substances. Although the direct greenhouse gases CO₂, CH₄, and N₂O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2014, concentrations of these greenhouse gases have increased globally by 43, 160, and 21 percent, respectively (IPCC 2013 and NOAA/ESRL 2016). 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 each 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 time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2013). Direct radiative effects occur when the gas itself is a greenhouse gas. The reference gas used is CO₂, and therefore GWP-

⁵ See <<http://www.ipcc-nccc.iges.or.jp/public/index.html>>.

⁶ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>>.

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

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.

weighted emissions are measured in million metric tons of CO₂ equivalent (MMT CO₂ Eq.).^{9,10} All gases in this Executive Summary are presented in units of MMT CO₂ Eq. Emissions by gas in unweighted mass tons are provided in the Trends chapter of this report.

UNFCCC reporting guidelines for national inventories require the use of GWP values from the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007).¹¹ To comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 GWP values, which have replaced the previously required use of *IPCC Second Assessment Report* (SAR) (IPCC 1996) GWP values in the Inventory. All estimates are provided throughout the report in both CO₂ equivalents and unweighted units. A comparison of emission values using the AR4 GWP values versus the 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 ₂ O	298
HFC-23	14,800
HFC-32	675
HFC-125	3,500
HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-4310mee	1,640
CF ₄	7,390
C ₂ F ₆	12,200
C ₄ F ₁₀	8,860
C ₆ F ₁₄	9,300
SF ₆	22,800
NF ₃	17,200

Source: IPCC (2007)

^a The CH₄ GWP 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 CO₂ is not included.

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

¹⁰ One teragram is equal to 10¹² grams or one million metric tons.

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

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

In 2014, total U.S. greenhouse gas emissions were 6,870.5 MMT or million metric tons CO₂ Eq. Total U.S. emissions have increased by 7.4 percent from 1990 to 2014, and emissions increased from 2013 to 2014 by 1.0 percent (70.5 MMT CO₂ Eq.). In 2014, relatively cool winter conditions led to an increase in fuels for the residential and commercial sectors for heating. Additionally, transportation emissions increased as a result of a small increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes. There also was an increase in industrial production across multiple sectors resulting in slight increases in industrial sector emissions. Lastly, since 1990, U.S. emissions have increased at an average annual rate of 0.3 percent. Figure ES-1 through Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual changes, and absolute change since 1990. Overall, net emissions in 2014 were 8.6 percent below 2005 levels as shown in Table ES-2.

Table ES-2 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2014.

Figure ES-1: U.S. Greenhouse Gas Emissions by Gas (MMT CO₂ Eq.)

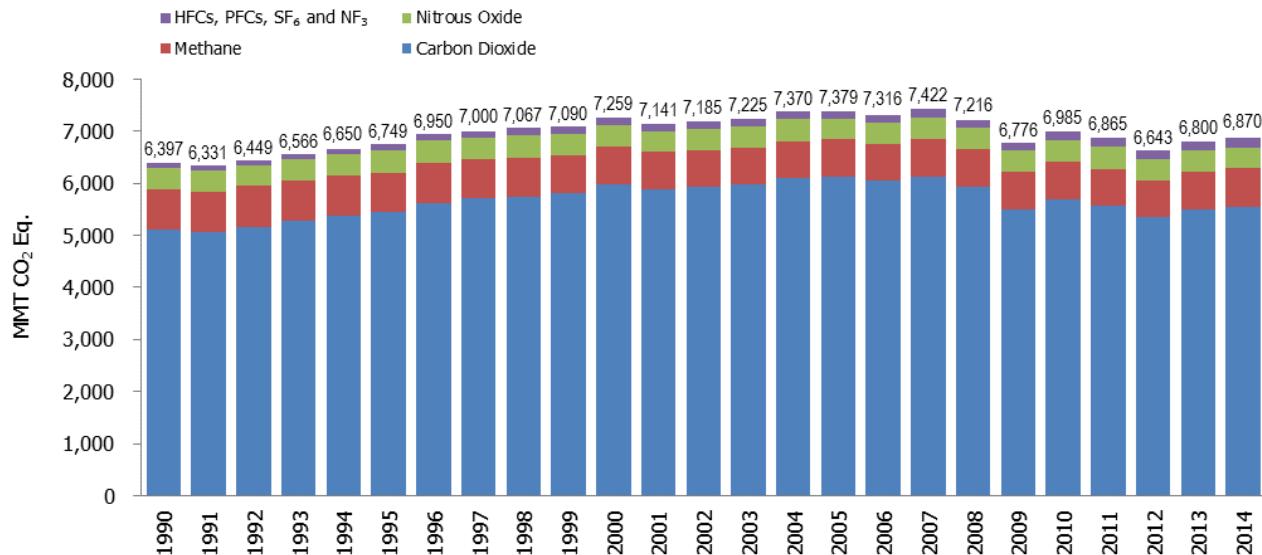


Figure ES-2: Annual Percent Change in U.S. Greenhouse Gas Emissions Relative to the Previous Year

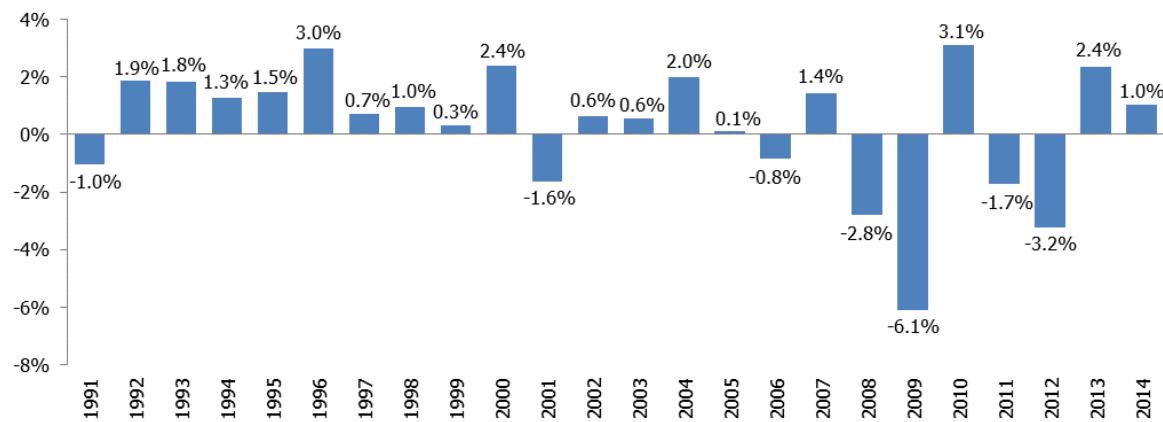


Figure ES-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0, MMT CO₂ Eq.)

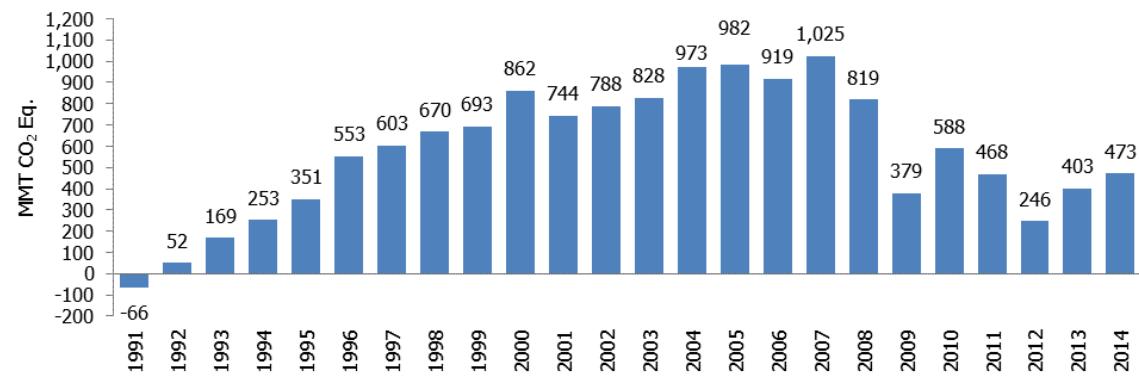


Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO ₂	5,115.1	6,122.7	5,688.8	5,559.5	5,349.2	5,502.6	5,556.0
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
<i>Electricity Generation</i>	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3
<i>Transportation</i>	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6
<i>Industrial</i>	842.5	828.0	775.5	773.3	782.9	812.2	813.3
<i>Residential</i>	338.3	357.8	334.6	326.8	282.5	329.7	345.1
<i>Commercial</i>	217.4	223.5	220.1	220.7	196.7	221.0	231.9
<i>U.S. Territories</i>	27.9	49.9	41.4	41.5	43.6	43.5	41.0
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Iron and Steel Production & Metallurgical Coke Production	99.7	66.5	55.7	59.9	54.2	52.2	55.4
Natural Gas Systems	37.7	30.1	32.4	35.7	35.2	38.5	42.4
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.6	27.4	27.2	26.3	26.5	26.4	26.5
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1

	1990	1995	2000	2005	2010	2014	2015
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Incineration of Waste	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Petroleum Systems	3.6	3.9	4.2	4.2	3.9	3.7	3.6
Aluminum Production	6.8	4.1	2.7	3.3	3.4	3.3	2.8
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
<i>Wood Biomass and Ethanol Consumption^a</i>	219.4	229.8	265.1	268.1	267.7	286.3	293.7
<i>International Bunker Fuels^b</i>	103.5	113.1	117.0	111.7	105.8	99.8	103.2
CH₄	773.9	717.4	722.4	717.4	714.4	721.5	730.8
Natural Gas Systems	206.8	177.3	166.2	170.1	172.6	175.6	176.1
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Petroleum Systems	38.7	48.8	54.1	56.3	58.4	64.7	68.1
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Wastewater Treatment	15.7	15.9	15.5	15.3	15.0	14.8	14.7
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Stationary Combustion	8.5	7.4	7.1	7.1	6.6	8.0	8.1
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3
Composting	0.4	1.9	1.8	1.9	1.9	2.0	2.1
Mobile Combustion	5.6	2.7	2.3	2.2	2.2	2.1	2.0
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	+	+	0.1	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
<i>International Bunker Fuels^b</i>	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N₂O	406.2	397.6	410.3	416.5	409.3	403.4	403.5
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Stationary Combustion	11.9	20.2	22.2	21.3	21.4	22.9	23.4
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Mobile Combustion	41.2	34.4	23.6	22.4	20.0	18.2	16.3
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4

Wastewater Treatment	3.4	4.3	4.5	4.7	4.8	4.8	4.8
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Composting	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.1	0.2	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
<i>International Bunker Fuels^b</i>	0.9	1.0	1.0	1.0	0.9	0.9	0.9
HFCs	46.6	119.9	149.4	154.3	155.9	158.9	166.7
Substitution of Ozone Depleting Substances ^c	0.3	99.7	141.2	145.3	150.2	154.6	161.2
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Magnesium Production and Processing	0.0	0.0	+	+	+	0.1	0.1
PFCs	24.3	6.7	4.5	7.0	6.0	5.8	5.6
Semiconductor Manufacture	2.8	3.2	2.7	3.5	3.1	2.9	3.0
Aluminum Production	21.5	3.4	1.9	3.5	2.9	3.0	2.5
SF₆	31.1	14.0	9.5	10.0	7.6	7.2	7.3
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.6	1.5	1.0
Semiconductor Manufacture	0.5	0.7	0.4	0.4	0.4	0.4	0.7
NF₃	+	0.5	0.6	0.7	0.6	0.6	0.5
Semiconductor Manufacture	+	0.5	0.6	0.7	0.6	0.6	0.5
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
LULUCF Emissions^d	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^e	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^f	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Emissions from Wood Biomass and Ethanol 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 Small amounts of PFC emissions also result from this source.

^d LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Agricultural Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^e Net CO₂ flux 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, Settlements Remaining Settlements, and Other*. Refer to Table ES-5 for a breakout of emissions and removals for Land Use, Land-Use Change, and Forestry by gas and source category.

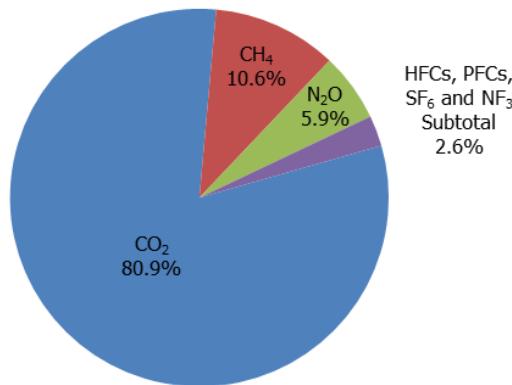
^f The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2014. Note, unless otherwise stated, all tables and figures provide total emissions without LULUCF. The primary greenhouse gas emitted by human activities in the United States was CO₂, representing approximately 80.9 percent of total greenhouse gas emissions. The largest source of CO₂, and of overall greenhouse gas emissions, was fossil fuel combustion. CH₄ emissions, which have decreased by 5.6 percent since 1990, resulted primarily from decomposition of wastes in landfills, enteric fermentation associated with domestic livestock, and natural gas systems. Agricultural soil management, manure management, mobile source fuel combustion and stationary fuel

combustion were the major sources of N₂O 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 resulted as a byproduct of primary aluminum production and from semiconductor manufacturing, electrical transmission and distribution systems accounted for most sulfur hexafluoride (SF₆) emissions, and semiconductor manufacturing is the only source of nitrogen trifluoride (NF₃) emissions.

Figure ES-4: 2014 U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO₂ Eq.)



Overall, from 1990 to 2014, total emissions of CO₂ increased by 440.9 MMT CO₂ Eq. (8.6 percent), while total emissions of CH₄ decreased by 43.0 MMT CO₂ Eq. (5.6 percent), and N₂O decreased by 2.7 MMT CO₂ Eq. (0.7 percent). During the same period, aggregate weighted emissions of HFCs, PFCs, SF₆ and NF₃ rose by 78.1 MMT CO₂ Eq. (76.6 percent). From 1990 to 2014, HFCs increased by 120.1 MMT CO₂ Eq. (257.9 percent), PFCs decreased by 18.7 MMT CO₂ Eq. (77.1 percent), SF₆ decreased by 23.7 MMT CO₂ Eq. (76.4 percent), and NF₃ increased by 0.4 MMT CO₂ Eq. (923.4 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF₆ and NF₃ are significant because many of these gases have extremely high global warming potentials and, in the cases of PFCs and SF₆, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, and landfilled yard trimmings and food scraps, which, in aggregate, offset 11.5 percent of total emissions in 2014. The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

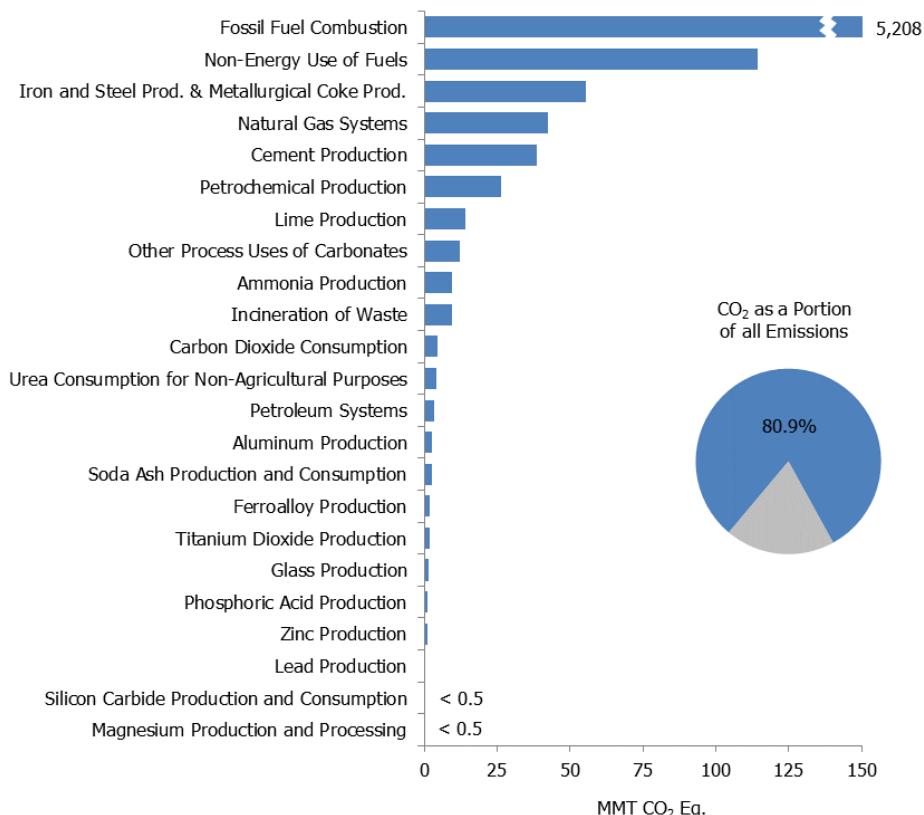
Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO₂ 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, carbon fluxes among these various reservoirs are roughly balanced.¹² Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO₂ have risen approximately 43 percent (IPCC 2013 and NOAA/ESRL 2016), principally due to the combustion of fossil fuels. Within the United States, fossil fuel combustion accounted for 93.7 percent of CO₂ emissions in 2014. Globally,

¹² The term “flux” is used to describe the net emissions of greenhouse gases accounting for both the emissions of CO₂ to and the removals of CO₂ from the atmosphere. Removal of CO₂ from the atmosphere is also referred to as “carbon sequestration.”

approximately 32,190 MMT of CO₂ were added to the atmosphere through the combustion of fossil fuels in 2013, of which the United States accounted for approximately 16 percent.¹³ Changes in land use and forestry practices can also emit CO₂ (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO₂ (e.g., through net additions to forest biomass). Although fossil fuel combustion is the greatest source of CO₂ emissions, there are 22 additional sources of CO₂ emissions (Figure ES-5).

Figure ES-5: 2014 Sources of CO₂ Emissions (MMT CO₂ Eq.)



Note: Fossil Fuel Combustion includes electricity generation, which also includes emissions of less than 0.05 MMT CO₂ Eq. from geothermal-based generation.

As the largest source of U.S. greenhouse gas emissions, CO₂ from fossil fuel combustion has accounted for approximately 76 percent of GWP-weighted emissions since 1990, and is approximately 76 percent of total GWP-weighted emissions in 2014. Emissions of CO₂ from fossil fuel combustion increased at an average annual rate of 0.4 percent from 1990 to 2014. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 25 years, (2) an overall growth in emissions from electricity generation and transportation activities, and (3) a general decline in the carbon intensity of fuels combusted for energy in recent years by most sectors of the economy. Between 1990 and 2014, CO₂ emissions from fossil fuel combustion increased from 4,740.7 MMT CO₂ Eq. to 5,208.2 MMT CO₂ Eq., a 9.9 percent total increase over the twenty-five-year period. From 2013 to 2014, these emissions increased by 50.6 MMT CO₂ Eq. (1.0 percent).

Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends. Changes in CO₂ emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes,

¹³ Global CO₂ emissions from fossil fuel combustion were taken from International Energy Agency *CO₂ Emissions from Fossil Fuels Combustion – Highlights* (2015). See <<https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015.pdf>>.

energy fuel choices, and seasonal temperatures. In the short term, the overall consumption of fossil fuels in the United States fluctuates primarily 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. In the long term, energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs), and behavioral choices (e.g., walking, bicycling, or telecommuting to work instead of driving).

Figure ES-6: 2014 CO₂ Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO₂ Eq.)

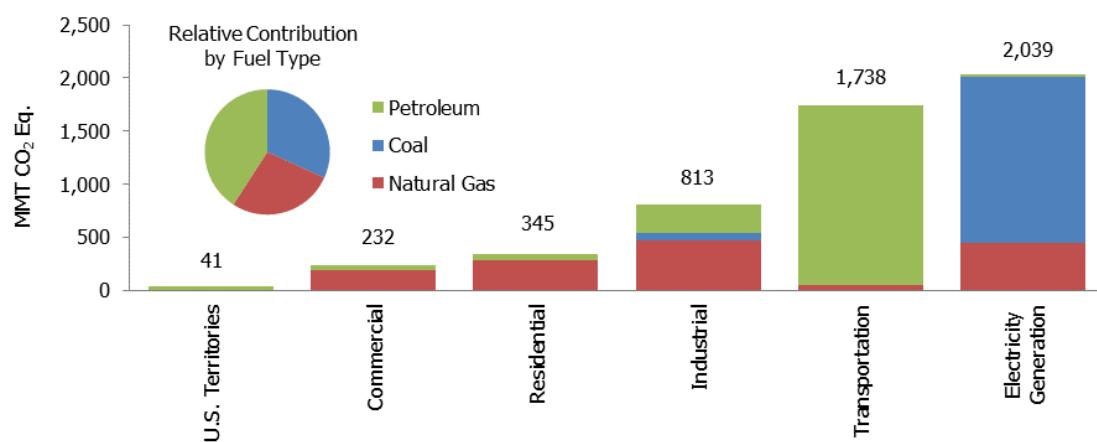
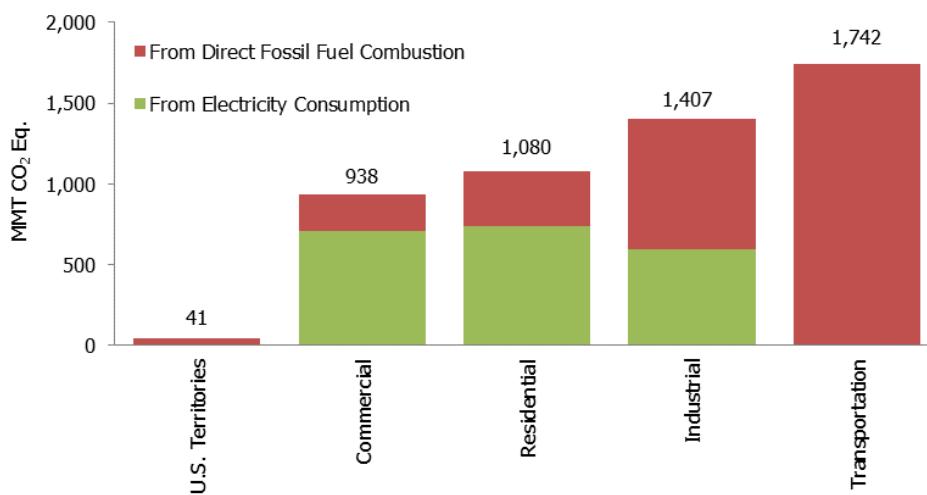


Figure ES-7: 2014 End-Use Sector Emissions of CO₂ from Fossil Fuel Combustion (MMT CO₂ Eq.)



The five major fuel consuming sectors contributing to CO₂ emissions from fossil fuel combustion are electricity generation, transportation, industrial, residential, and commercial. CO₂ emissions are produced by the electricity generation sector as they consume fossil fuel to provide electricity to one of the other four sectors, or “end-use”

sectors. For the discussion below, electricity generation emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity consumption. This method of distributing emissions assumes that each end-use sector consumes electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electricity generation are also addressed separately after the end-use sectors have been discussed.

Note that emissions from U.S. Territories are calculated separately due to a lack of specific consumption data for the individual end-use sectors. Figure ES-6, Figure ES-7, and Table ES-3 summarize CO₂ emissions from fossil fuel combustion by end-use sector.

Table ES-3: CO₂ Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation	1,496.8	1,891.8	1,732.7	1,711.9	1,700.6	1,717.0	1,741.7
Combustion	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6
Electricity	3.0	4.7	4.5	4.3	3.9	4.0	4.1
Industrial	1,529.2	1,564.6	1,416.5	1,398.0	1,375.7	1,407.0	1,406.8
Combustion	842.5	828.0	775.5	773.3	782.9	812.2	813.3
Electricity	686.7	736.6	641.0	624.7	592.8	594.7	593.6
Residential	931.4	1,214.1	1,174.6	1,117.5	1,007.8	1,064.6	1,080.3
Combustion	338.3	357.8	334.6	326.8	282.5	329.7	345.1
Electricity	593.0	856.3	840.0	790.7	725.3	734.9	735.2
Commercial	755.4	1,026.8	993.0	958.8	897.0	925.5	938.4
Combustion	217.4	223.5	220.1	220.7	196.7	221.0	231.9
Electricity	538.0	803.3	772.9	738.0	700.3	704.5	706.5
U.S. Territories^a	27.9	49.9	41.4	41.5	43.6	43.5	41.0
Total	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
Electricity Generation	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3

^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.

Notes: Combustion-related emissions from electricity generation are allocated based on aggregate national electricity consumption by each end-use sector. Totals may not sum due to independent rounding.

Transportation End-Use Sector. When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 33.4 percent of U.S. CO₂ emissions from fossil fuel combustion in 2014. The largest sources of transportation CO₂ emissions in 2014 were passenger cars (42.4 percent), medium- and heavy-duty trucks (23.1 percent), light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (17.8 percent), commercial aircraft (6.6 percent), pipelines (2.7 percent), rail (2.6 percent), and ships and boats (1.6 percent). Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO₂, CH₄, N₂O, and HFCs.

In terms of the overall trend, from 1990 to 2014, total transportation CO₂ emissions rose by 16 percent 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 2014). The number of VMT by light-duty motor vehicles (i.e., passenger cars and light-duty trucks) increased 37 percent from 1990 to 2014, 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. 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.

Industrial End-Use Sector. Industrial CO₂ emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 27 percent of CO₂ from fossil fuel combustion in 2014. Approximately 58 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from consuming electricity for motors, electric furnaces, ovens, lighting, and other applications. In contrast to the other

end-use sectors, emissions from industry have steadily declined 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 21 and 18 percent, respectively, of CO₂ emissions from fossil fuel combustion in 2014. Both sectors relied heavily on electricity for meeting energy demands, with 68 and 75 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Emissions from the residential and commercial end-use sectors have increased by 16 percent and 24 percent since 1990, respectively, due to increasing electricity consumption for lighting, heating, air conditioning, and operating appliances.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators consumed 34 percent of total U.S. energy uses from fossil fuels and emitted 39 percent of the CO₂ from fossil fuel combustion in 2014. The type of fuel combusted by electricity generators has a significant effect on their emissions. For example, some electricity is generated through non-fossil fuel options such as nuclear, hydroelectric, or geothermal energy. Including all electricity generation modes, generators relied on coal for approximately 39 percent of their total energy requirements in 2014.¹⁴ In addition, the coal used by electricity generators accounted for 93 percent of all coal consumed for energy in the United States in 2014.¹⁵ Recently, a decrease in the carbon intensity of fuels consumed to generate electricity has occurred due to a decrease in coal consumption, and increased natural gas consumption and other generation sources. Including all electricity generation modes, electricity generators used natural gas for approximately 27 percent of their total energy requirements in 2014.¹⁶ Across the time series, changes in electricity demand and the carbon intensity of fuels used for electricity generation have a significant impact on CO₂ emissions.

Other significant CO₂ trends included the following:

- Carbon dioxide emissions from non-energy use of fossil fuels decreased by 3.8 MMT CO₂ Eq. (3.2 percent) from 1990 through 2014. Emissions from non-energy uses of fossil fuels were 114.3 MMT CO₂ Eq. in 2014, which constituted 2.1 percent of total national CO₂ emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production have declined by 44.3 MMT CO₂ Eq. (44.5 percent) from 1990 through 2014, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Carbon dioxide emissions from ammonia production (9.4 MMT CO₂ Eq. in 2014) decreased by 3.6 MMT CO₂ Eq. (27.7 percent) 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.
- Total net flux from (i.e., net CO₂ removals) from Land Use, Land-Use Change, and Forestry increased by 34.1 MMT CO₂ Eq. (4.5 percent) from 1990 through 2014. This increase was primarily due to an increase in the rate of net C accumulation in forest and urban tree carbon stocks. Annual carbon accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of carbon accumulation in urban trees increased.

Box ES-2: 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.¹⁷ Several recent studies have measured emissions at the national or regional level (e.g., Petron 2012, Miller et al. 2013) with results that differ from EPA's estimate of emissions. A recent study reviewed technical literature on CH₄ emissions and estimated CH₄ emissions

¹⁴ See <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.

¹⁵ See Table 6.2 Coal Consumption by Sector of EIA 2016.

¹⁶ See <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.

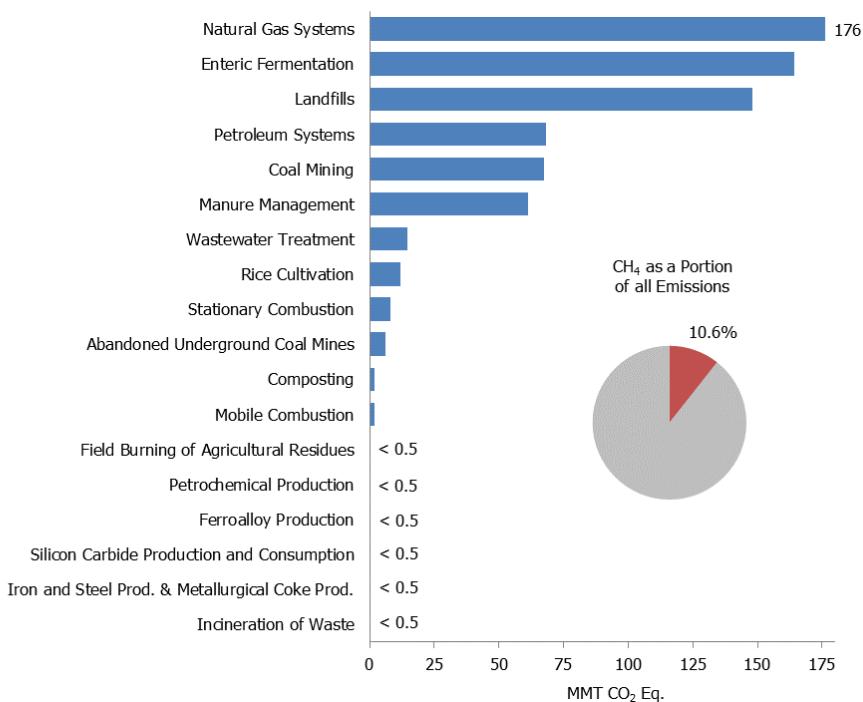
¹⁷ See <<http://www.ipcc-nngip.iges.or.jp/public/index.html>>.

from all anthropogenic sources (e.g., livestock, oil and gas, waste emissions) to be greater than EPA's estimate (Brandt et al. 2014). EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for greenhouse gas emissions could assist in improving the understanding of inventory estimates. An area of particular interest in EPA's outreach efforts is how these data can be used in a manner consistent with this Inventory report's transparency on 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 working with the research community on ambient measurement and remote sensing techniques to improve national greenhouse gas inventories, EPA relies upon guidance from the IPCC on the use of measurements and modeling to validate emission inventories.¹⁸

Methane Emissions

Methane (CH_4) is 25 times as effective as CO_2 at trapping heat in the atmosphere (IPCC 2007). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 160 percent (IPCC 2013 and CDIAC 2015). Anthropogenic sources of CH_4 include natural gas and petroleum systems, agricultural activities, landfills, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-8).

Figure ES-8: 2014 Sources of CH_4 Emissions (MMT CO_2 Eq.)



Some significant trends in U.S. emissions of CH_4 include the following:

- Natural gas systems were the largest anthropogenic source category of CH_4 emissions in the United States in 2014 with 176.1 MMT CO_2 Eq. of CH_4 emitted into the atmosphere. Those emissions have decreased by 30.6 MMT CO_2 Eq. (14.8 percent) since 1990. The decrease in CH_4 emissions is largely due to the decrease in emissions from transmission, storage, and distribution. The decrease in transmission and storage

¹⁸ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1003_Uncertainty%20meeting_report.pdf>.

emissions is largely due to reduced compressor station emissions (including emissions from compressors and fugitives). The decrease in distribution emissions is largely attributed to increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating (M&R) stations.

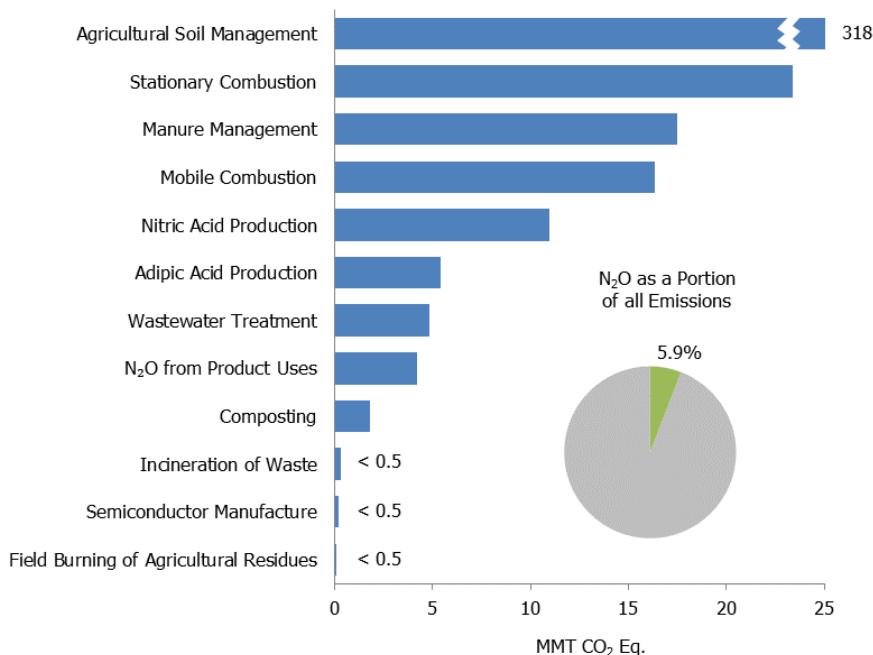
- Petroleum systems are the fourth anthropogenic source of CH₄ emissions in the United States (68.1 MMT CO₂ Eq.), accounting for 9.3 percent of total CH₄ emissions in 2014. From 1990 to 2014, CH₄ emissions from petroleum systems increased by 29.4 MMT CO₂ Eq. (or 76 percent). This increase is due primarily to increases in emissions from production equipment.
- Enteric fermentation is the second largest anthropogenic source of CH₄ emissions in the United States. In 2014, enteric fermentation CH₄ emissions were 164.3 MMT CO₂ Eq. (22.5 percent of total CH₄ emissions), which represents an increase of 0.1 MMT CO₂ Eq. (0.1 percent) since 1990. This increase in emissions from 1990 to 2014 generally follows the increasing trends in cattle populations. 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 underwent increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased.
- Landfills are the third largest anthropogenic source of CH₄ emissions in the United States (148.0 MMT CO₂ Eq.), accounting for 20.2 percent of total CH₄ emissions in 2014. From 1990 to 2014, CH₄ emissions from landfills decreased by 31.6 MMT CO₂ Eq. (17.6 percent), with small increases occurring in some interim years. This downward trend in emissions can be attributed to a 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series (EPA 2015b) and an increase in the amount of landfill gas collected and combusted (i.e., used for energy or flared),¹⁹ which has more than offset the additional CH₄ emissions resulting from an increase in the amount of municipal solid waste landfilled.
- Methane emissions from manure management increased by 64.7 percent since 1990, from 37.2 MMT CO₂ Eq. in 1990 to 61.2 MMT CO₂ Eq. in 2014. The majority of this increase was from swine and dairy cow manure, since the general trend in manure management is one of increasing use of liquid systems, which tends to produce greater CH₄ emissions. The increase in liquid systems is the combined result of a shift to larger facilities, and to facilities in the West and Southwest, all of which tend to use liquid systems. Also, new regulations limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site.

Nitrous Oxide Emissions

Nitrous oxide (N₂O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy-related, industrial, and waste management fields. While total N₂O emissions are much lower than CO₂ emissions, N₂O is approximately 300 times more powerful than CO₂ at trapping heat in the atmosphere (IPCC 2007). Since 1750, the global atmospheric concentration of N₂O has risen by approximately 21 percent (IPCC 2013 and CDIAC 2015). The main anthropogenic activities producing N₂O in the United States are agricultural soil management, stationary fuel combustion, fuel combustion in motor vehicles, manure management, and nitric acid production (see Figure ES-9).

¹⁹ Carbon dioxide emissions from landfills are not included specifically in summing waste 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.

Figure ES-9: 2014 Sources of N₂O Emissions (MMT CO₂ Eq.)



Some significant trends in U.S. emissions of N₂O include the following:

- Agricultural soils accounted for approximately 78.9 percent of N₂O emissions and 4.6 percent of total emissions in the United States in 2014. Estimated emissions from this source in 2014 were 318.4 MMT CO₂ Eq. Annual N₂O emissions from agricultural soils fluctuated between 1990 and 2014, although overall emissions were 5.0 percent higher in 2014 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.
- Nitrous oxide emissions from stationary combustion increased 11.5 MMT CO₂ Eq. (96.4 percent) from 1990 through 2014. Nitrous oxide emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.
- In 2014, total N₂O emissions from manure management were estimated to be 17.5 MMT CO₂ Eq.; emissions were 14.0 MMT CO₂ Eq. in 1990. These values include both direct and indirect N₂O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N₂O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N₂O emissions showed a 24.9 percent increase from 1990 to 2014 and a 0.1 percent decrease from 2013 through 2014. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.
- Nitrous oxide emissions from mobile combustion decreased 24.9 MMT CO₂ Eq. (60.4 percent) from 1990 through 2014, primarily as a result of N₂O national emission control standards and emission control technologies for on-road vehicles.
- Nitrous oxide emissions from adipic acid production were 5.4 MMT CO₂ Eq. in 2014, and have decreased significantly since 1990 due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Emissions from adipic acid production have decreased by 64.2 percent since 1990 and by 67.8 percent since a peak in 1995.

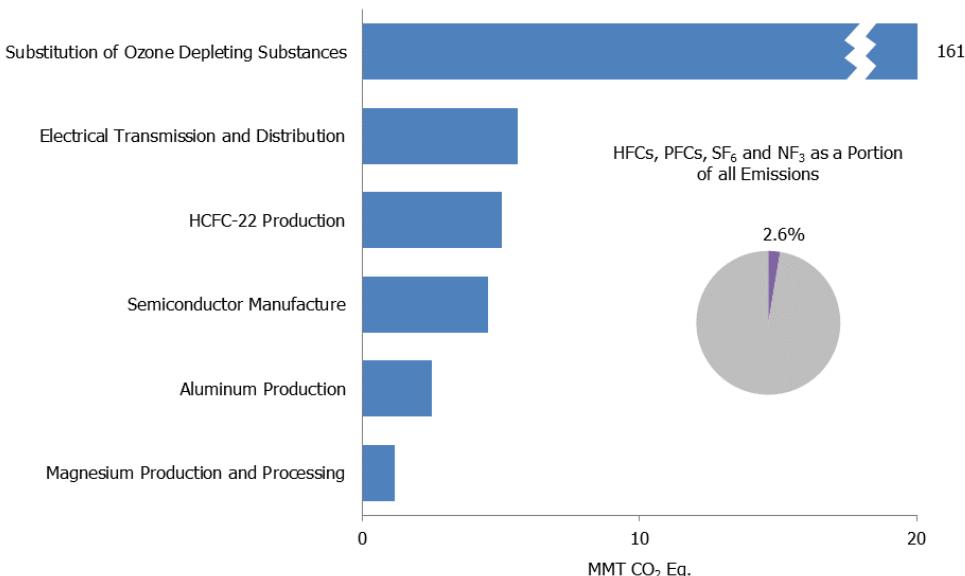
HFC, PFC, SF₆, and NF₃ Emissions

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are families of 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 and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under the *Montreal Protocol on Substances that Deplete the Ozone Layer*.

These compounds, however, along with SF₆ and NF₃, are potent greenhouse gases. In addition to having high global warming potentials, SF₆ 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).

Other emissive sources of these gases include HCFC-22 production, electrical transmission and distribution systems, semiconductor manufacturing, aluminum production, and magnesium production and processing (see Figure ES-10).

Figure ES-10: 2014 Sources of HFCs, PFCs, SF₆, and NF₃ Emissions (MMT CO₂ Eq.)



Some significant trends in U.S. HFC, PFC, SF₆, and NF₃ emissions include the following:

- Emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) have been consistently increasing, from small amounts in 1990 to 161.2 MMT CO₂ Eq. in 2014. This increase was in large part the result of efforts to phase out CFCs and other ODS in the United States. In the short term, this trend is expected to continue, and will likely continue over the next decade as hydrochlorofluorocarbons (HCFCs), which are interim substitutes in many applications, are themselves phased out under the provisions of the *Copenhagen Amendments to the Montreal Protocol*.
- GWP-weighted PFC, HFC, SF₆, and NF₃ emissions from semiconductor manufacture have increased by 27.4 percent from 1990 to 2014, due to industrial growth and the adoption of emission reduction technologies. Within that time span, emissions peaked in 1999, the initial year of EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, but have since declined to 4.5 MMT CO₂ Eq. in 2014 (a 49.8 percent decrease relative to 1999).
- Sulfur hexafluoride emissions from electric power transmission and distribution systems decreased by 77.9 percent (19.8 MMT CO₂ Eq.) from 1990 to 2014. There are two potential causes for this decrease: (1) a sharp increase in the price of SF₆ during the 1990s and (2) a growing awareness of the environmental

impact of SF₆ emissions through programs such as EPA's SF₆ Emission Reduction Partnership for Electric Power Systems.

- Perfluorocarbon emissions from aluminum production decreased by 88.2 percent (18.9 MMT CO₂ Eq.) from 1990 to 2014. 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.

ES.3. Overview of Sector Emissions and Trends

In accordance with the UNFCCC decision to set the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) as the standard for Annex I countries at the Nineteenth Conference of the Parties (UNFCCC 2014), Figure ES-11 and Table ES-4 aggregate emissions and sinks by the sectors defined by those guidelines. Over the twenty-five-year period of 1990 to 2014, total emissions in the Energy, Industrial Processes and Product Use, and Agriculture grew by 421.3 MMT CO₂ Eq. (7.9 percent), 38.3 MMT CO₂ Eq. (11.2 percent), and 41.6 MMT CO₂ Eq. (7.8 percent), respectively. Over the same period, total emissions in the Waste sector decreased by 27.9 MMT CO₂ Eq. (14.0 percent) and estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (magnitude of emissions plus CO₂ removals from all LULUCF source categories) decreased by 24.5 MMT CO₂ Eq. (3.3 percent).

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO₂ Eq.)

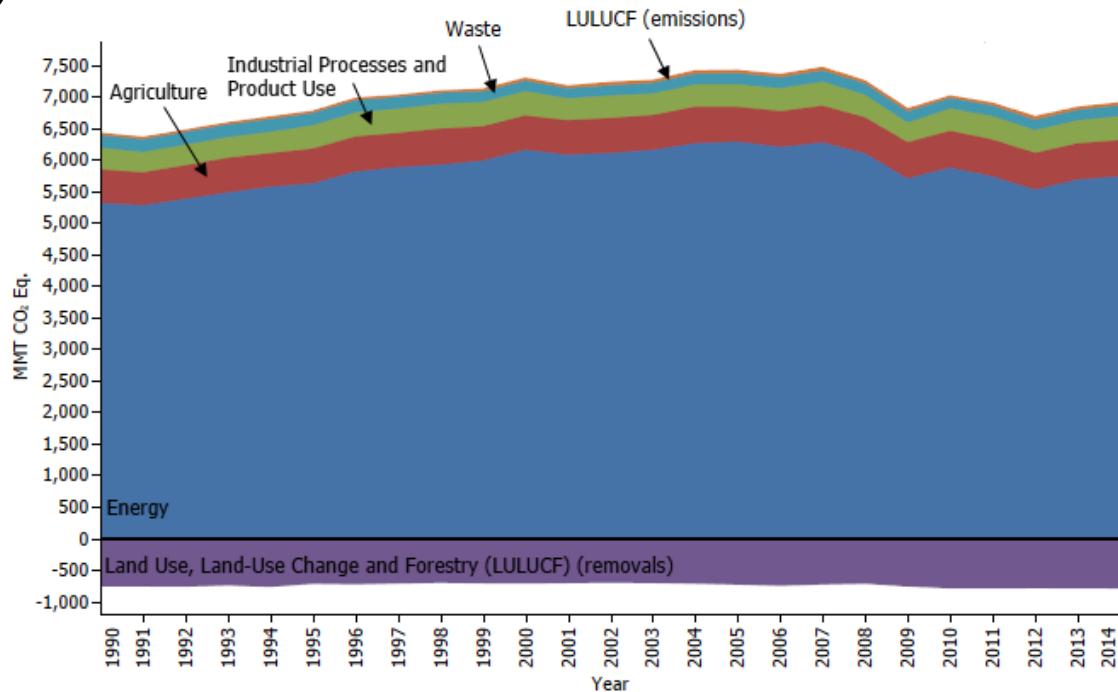


Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO₂ Eq.)

Chapter/IPCC Sector	1990	2005	2010	2011	2012	2013	2014
Energy	5,324.9	6,294.5	5,884.6	5,744.0	5,533.9	5,693.5	5,746.2
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2

Natural Gas Systems	244.5	207.4	198.6	205.7	207.8	214.0	218.5
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Petroleum Systems	42.3	52.8	58.2	60.5	62.2	68.4	71.7
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Stationary Combustion	20.4	27.6	29.2	28.4	28.0	30.9	31.5
Mobile Combustion	46.9	37.1	25.9	24.7	22.2	20.3	18.4
Incineration of Waste	8.4	12.8	11.4	10.9	10.7	9.7	9.7
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3
Industrial Processes and Product Use	340.9	354.3	353.0	370.5	360.1	363.5	379.2
Substitution of Ozone Depleting Substances	0.3	99.7	141.2	145.3	150.2	154.6	161.2
Iron and Steel Production & Metallurgical Coke Production	99.7	66.6	55.7	59.9	54.2	52.2	55.4
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.8	27.5	27.3	26.4	26.5	26.5	26.6
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4
Aluminum Production	28.3	7.6	4.6	6.8	6.4	6.2	5.4
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0
Semiconductor Manufacture	3.6	4.7	4.0	5.1	4.5	4.2	4.7
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.7	1.5	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	532.0	552.2	582.3	583.1	583.3	575.3	573.6
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	51.1	72.9	78.1	78.9	81.2	78.9	78.7
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Waste	199.3	177.8	165.5	167.8	165.7	167.8	171.4
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Wastewater Treatment	19.0	20.2	19.9	19.9	19.8	19.6	19.5
Composting	0.7	3.5	3.5	3.5	3.7	3.9	3.9
Total Emissions^a	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
Land Use, Land-Use Change, and Forestry	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Forest Land	(718.7)	(675.8)	(736.5)	(725.6)	(717.4)	(726.8)	(730.0)
Cropland	38.5	25.9	34.0	17.1	21.1	21.1	22.3
Grassland	26.2	39.8	32.0	43.0	43.9	44.1	44.2

Wetlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Settlements	(59.0)	(78.2)	(83.8)	(84.8)	(85.8)	(87.1)	(88.2)
Other	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
Net Emissions (Sources and Sinks)^b	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

^a Total emissions without LULUCF.

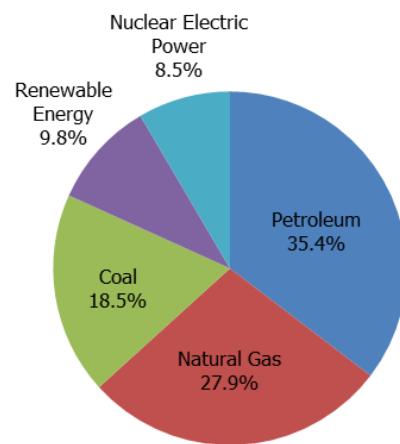
^b Total emissions with LULUCF.

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

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO₂ emissions for the period of 1990 through 2014. In 2014, approximately 82 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 18 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12). Energy-related activities are also responsible for CH₄ and N₂O emissions (45 percent and 10 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 83.6 percent of total U.S. greenhouse gas emissions in 2014.

Figure ES-12: 2014 U.S. Energy Consumption by Energy Source (Percent)



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.

Greenhouse gas emissions are produced as the by-products of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO₂, CH₄, and N₂O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production, urea consumption, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and consumption, titanium dioxide production, phosphoric acid production, ferroalloy production, CO₂ consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, zinc production, and N₂O from product uses. Industrial processes also release HFCs, PFCs, SF₆, and

NF_3 . In addition to their use as ODS substitutes, HFCs, PFCs, SF_6 , NF_3 , and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Overall, emission sources in the Industrial Process and Product Use chapter account for 5.5 percent of U.S. greenhouse gas emissions in 2014.

Agriculture

The Agriculture chapter contains anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and agricultural CO_2 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: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues. CH_4 and N_2O were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represented 22.5 percent and 8.4 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2014. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2014, accounting for 78.9 percent. In 2014, emission sources accounted for in the Agricultural chapters were responsible for 8.3 percent of total U.S. greenhouse gas emissions.

Land Use, Land-Use Change, and Forestry

The Land Use, Land-Use Change, and Forestry chapter contains emissions of CH_4 and N_2O , and emissions and removals of CO_2 from forest management, other land-use activities, and land-use change. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps resulted in a net removal of CO_2 (C sequestration) in the United States. Forests (including vegetation, soils, and harvested wood) accounted for 87 percent of total 2014 CO_2 removals, urban trees accounted for 11 percent, landfilled yard trimmings and food scraps accounted for 1.4 percent, and mineral and organic soil C stock changes from *Cropland Remaining Cropland* accounted for 1.0 percent of the total CO_2 removals in 2014. The net forest sequestration is a result of net forest growth and increasing forest area, as well as a net accumulation of C stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth in these areas. In agricultural soils, mineral and organic soils sequester approximately as much C as is emitted from these soils through liming and urea fertilization. The mineral soil C sequestration is largely due to the conversion of cropland to permanent pastures and hay production, a reduction in summer fallow areas in semi-arid areas, an increase in the adoption of conservation tillage practices, and an increase in the amounts of organic fertilizers (i.e., manure and sewage sludge) applied to agriculture lands. The landfilled yard trimmings and food scraps net sequestration is due to the long-term accumulation of yard trimming carbon and food scraps in landfills.

LULUCF activities in 2014 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 787.0 MMT CO_2 Eq. (Table ES-5).²⁰ This represents an offset of 11.5 percent of total (i.e., gross) greenhouse gas emissions in 2014. Emissions from land use, land-use change, and forestry activities in 2014 are 24.6 MMT CO_2 Eq. and represent 0.4 percent of total greenhouse gas emissions.²¹ Between 1990 and 2014, total C sequestration in the LULUCF sector increased by 4.5 percent, primarily due to an increase in the rate of net C accumulation in forest and urban tree C stocks. Annual C accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of annual C accumulation increased in urban trees.

Carbon dioxide removals are presented in Table ES-5 along with CO_2 , CH_4 , and N_2O emissions for LULUCF source categories. Liming and urea fertilization in 2014 resulted in CO_2 emissions of 8.7 MMT CO_2 Eq. (8,653 kt). Lands

²⁰ Net CO_2 flux 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, Settlements Remaining Settlements, and Other*.

²¹ LULUCF emissions include the CO_2 , CH_4 , and N_2O emissions reported for Non- CO_2 Emissions from Forest Fires, N_2O Fluxes from Forest Soils, CO_2 Emissions from Liming, CO_2 Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N_2O Fluxes from Settlement Soils.

undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO₂ emissions of 0.8 MMT CO₂ Eq. (842 kt) and CH₄ and N₂O emissions of less than 0.05 MMT CO₂ Eq. each. The application of synthetic fertilizers to forest soils in 2014 resulted in N₂O emissions of 0.5 MMT CO₂ Eq. (2 kt). N₂O emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, N₂O emissions from fertilizer application to settlement soils in 2014 accounted for 2.4 MMT CO₂ Eq. (8 kt). This represents an increase of 78 percent since 1990. Forest fires in 2014 resulted in CH₄ emissions of 7.3 MMT CO₂ Eq. (294 kt), and in N₂O emissions of 4.8 MMT CO₂ Eq. (16 kt).

Table ES-5: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO₂ Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO ₂ Flux ^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
Forest Land Remaining Forest Land ^b	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Land Converted to Forest Land	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Cropland Remaining Cropland	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
Land Converted to Cropland	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Grassland Remaining Grassland	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Land Converted to Grassland	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Settlements Remaining Settlements	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
CO₂	8.1	9.0	9.6	8.9	11.0	9.0	9.5
Cropland Remaining Cropland: CO ₂ Emissions from Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Cropland Remaining Cropland: CO ₂ Emissions from Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
CH₄	3.3	9.9	3.3	6.6	11.1	7.3	7.4
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	3.3	9.9	3.3	6.6	11.1	7.3	7.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	3.6	9.3	5.0	7.3	10.3	7.7	7.7
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	2.2	6.5	2.2	4.4	7.3	4.8	4.8
Settlements Remaining Settlements: N ₂ O Fluxes from Settlement Soils ^c	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Forest Land Remaining Forest Land: N ₂ O Fluxes from Forest Soils ^d	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions^e	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^f	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Net CO₂ flux 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*, *Settlements Remaining Settlements*, and *Other*.

^b Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^c Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^d Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^e LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^f The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

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 in the Waste chapter, accounting for 86.3 percent of this chapter's emissions, and 20.2 percent of total U.S. CH₄ emissions.²² Additionally, wastewater treatment accounts for 11.4 percent of Waste emissions, 2.0 percent of U.S. CH₄ emissions, and 1.2 percent of U.S. N₂O emissions. Emissions of CH₄ and N₂O from composting are also accounted for in this chapter, generating emissions of 2.1 MMT CO₂ Eq. and 1.8 MMT CO₂ Eq., respectively. Overall, emission sources accounted for in the Waste chapter generated 2.5 percent of total U.S. greenhouse gas emissions in 2014.

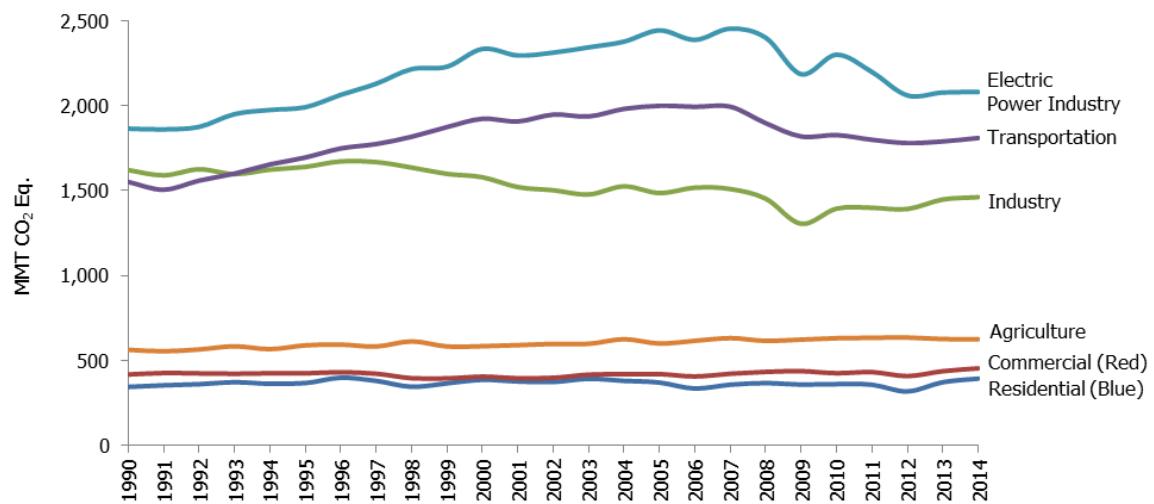
ES.4. Other Information

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; Industrial Processes and Product Use; Agriculture; LULUCF; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following economic sectors: residential, commercial, industry, transportation, electricity generation, agriculture, and U.S. Territories.

Table ES-6 summarizes emissions from each of these economic sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2014.

Figure ES-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq.)



²² 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.

Table ES-6: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq.)

Economic Sectors	1990	2005	2010	2011	2012	2013	2014
Electric Power Industry	1,864.8	2,443.9	2,300.5	2,198.1	2,060.7	2,078.0	2,080.7
Transportation	1,551.3	1,999.6	1,827.4	1,799.6	1,780.4	1,789.9	1,810.3
Industry	1,620.9	1,486.2	1,394.5	1,399.0	1,392.1	1,448.2	1,461.7
Agriculture	1,620.9	563.4	600.2	631.1	633.7	635.4	626.3
Commercial	363.4	418.1	420.3	425.5	432.1	408.5	437.5
Residential	418.1	344.9	370.4	361.2	357.6	318.4	372.6
U.S. Territories	33.9	33.7	58.2	45.3	45.4	47.6	47.5
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
LULUCF Sector Total^a	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

Note: Total emissions presented without LULUCF. Total net emissions presented with LULUCF.

^a The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Using this categorization, emissions from electricity generation accounted for the largest portion (30 percent) of U.S. greenhouse gas emissions in 2014. Transportation activities, in aggregate, accounted for the second largest portion (26 percent), while emissions from industry accounted for the third largest portion (21 percent) of U.S. greenhouse gas emissions in 2014. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been due to 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 22 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 9 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N₂O emissions from agricultural soil management and CH₄ emissions from enteric fermentation. The commercial and residential sectors accounted for 7 percent and 6 percent of emissions, respectively, and U.S. Territories accounted for 1 percent of emissions; emissions from these sectors primarily consisted of CO₂ emissions from fossil fuel combustion. CO₂ 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, and landfilling of yard trimmings.

Electricity is ultimately consumed in the economic sectors described above. Table ES-7 presents greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electricity generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.²³ These source categories include CO₂ from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO₂ and N₂O from incineration of waste, CH₄ and N₂O from stationary sources, and SF₆ from electrical transmission and distribution systems.

When emissions from electricity are distributed among these sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (29 percent and 26 percent, respectively) in 2014. The residential and commercial sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2014. Emissions from these sectors increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption (e.g., lighting, appliances). In all sectors except agriculture, CO₂ accounts for more than 80 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Figure ES-14 shows the trend in these emissions by sector from 1990 to 2014.

²³ Emissions were not distributed to U.S. Territories, since the electricity generation sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Table ES-7: U.S. Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (MMT CO₂ Eq.)

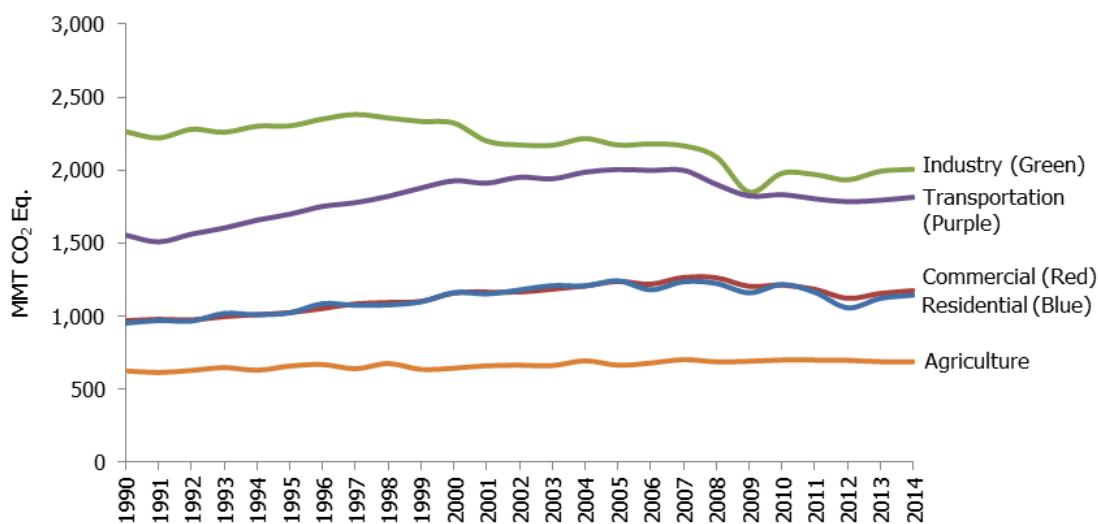
Implied Sectors	1990	2005	2010	2011	2012	2013	2014
Industry	2,262.9	2,171.9	1,979.1	1,970.0	1,934.0	1,992.5	2,005.7
Transportation	1,554.4	2,004.4	1,832.0	1,803.9	1,784.3	1,794.0	1,814.5
Commercial	969.1	1,238.0	1,212.8	1,183.9	1,122.1	1,155.8	1,174.7
Residential	952.2	1,242.1	1,216.9	1,163.1	1,057.5	1,121.9	1,143.8
Agriculture	624.8	664.2	699.5	699.1	697.5	688.3	687.0
U.S. Territories	33.7	58.2	45.3	45.4	47.6	47.5	44.7
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
LULUCF Sector Total^a	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

^a The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

Notes: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector.

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

Figure ES-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors (MMT CO₂ Eq.)



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

Total 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 consumption, 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 electricity consumption, because the electric power industry—utilities and non-utilities combined—was the largest source of U.S. greenhouse gas emissions in 2014; (4) emissions per unit of total gross domestic product as a measure of national economic activity; and (5) 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. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.3 percent since 1990. Since 1990, this rate is slightly slower than that for total energy and for fossil fuel consumption, and

much slower than that for electricity consumption, overall gross domestic product and national population (see Figure ES-15).

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

Variable	1990	2005	2010	2011	2012	2013	2014	Avg. Annual Growth Rate
Greenhouse Gas Emissions ^a	100	115	109	107	104	106	107	0.3%
Energy Consumption ^b	100	118	116	115	112	116	117	0.7%
Fossil Fuel Consumption ^b	100	119	112	110	107	110	111	0.5%
Electricity Consumption ^b	100	134	137	137	135	136	138	1.4%
GDP ^c	100	159	165	168	171	174	178	2.5%
Population ^d	100	118	124	125	126	126	127	1.0%

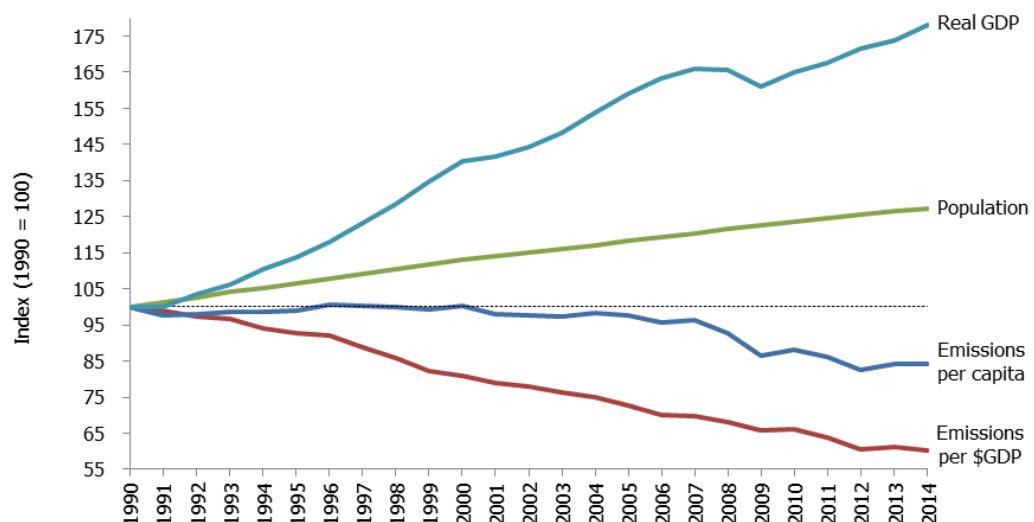
^a GWP-weighted values

^b Energy content-weighted values (EIA 2016)

^c Gross Domestic Product in chained 2009 dollars (BEA 2016)

^d U.S. Census Bureau (2015)

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)



Source: BEA (2016), U.S. Census Bureau (2015), and emission estimates in this report.

Key Categories

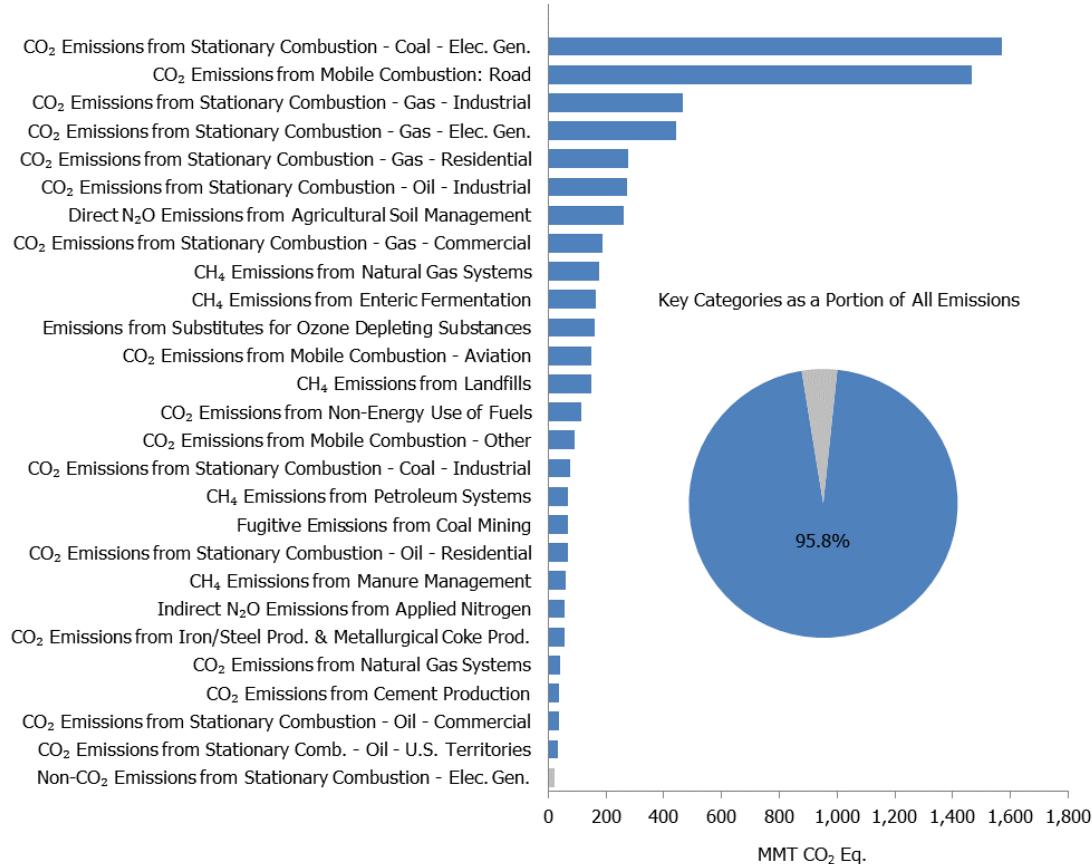
The 2006 IPCC Guidelines (IPCC 2006) defines a key category as a “[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country’s total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals.”²⁴ By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission estimates is prepared, a thorough investigation of key categories must also account for the influence of trends of

²⁴ See Chapter 4 “Methodological Choice and Identification of Key Categories” in IPCC (2006). See <<http://www.ipccnggip.iges.or.jp/public/2006gl/vol1.html>>

individual source and sink categories. Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses.

Figure ES-16 presents 2014 emission estimates for the key categories as defined by a level analysis (i.e., the contribution of each source or sink category to the total inventory level). The UNFCCC reporting guidelines request that key category analyses be reported at an appropriate level of disaggregation, which may lead to source and sink category names which differ from those used elsewhere in the Inventory report. For more information regarding key categories, see Section 1.5 – Key Categories and Annex 1.

Figure ES-16: 2014 Key Categories (MMT CO₂ Eq.)



Note: For a complete discussion of the key category analysis, see Annex 1. Blue bars indicate either an Approach 1, or Approach 1 and Approach 2 level assessment key category. Gray bars indicate solely an Approach 2 level assessment key category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks to continually improve the quality, transparency, and credibility 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. While QA/QC has always been an integral part of the U.S. national system for Inventory development, the procedures followed for the current Inventory have been formalized in accordance with the *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC Management Plan) for the Inventory and the UNFCCC reporting guidelines.

Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete inventory of greenhouse gas emissions and removals. Some of the current estimates, such as those for CO₂ emissions from energy-related activities and cement processing, are considered to have low uncertainties. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty associated with the estimates presented. Acquiring a better understanding of the uncertainty associated with inventory estimates is an important step in helping to prioritize future work and improve the overall quality of the Inventory. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines* (IPCC 2006) and require that countries provide single estimates of uncertainty for source and sink categories.

Currently, a qualitative discussion of uncertainty is presented for all source and sink categories. Within the discussion of each emission source, specific factors affecting the uncertainty surrounding the estimates are discussed. Most sources also contain a quantitative uncertainty assessment, in accordance with UNFCCC reporting guidelines.

Box ES-4: Recalculations of Inventory Estimates

Each year, emission and sink estimates are recalculated and revised for all years in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the 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; new inventory methods become available; and for correction of errors.” 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.

In each Inventory report, the results of all methodology changes and historical data updates are presented in the Recalculations and Improvements chapter; detailed descriptions of each recalculation are contained within each source's description contained in the report, if applicable. In general, when methodological changes have been implemented, the entire time series (in the case of the most recent Inventory report, 1990 through 2013) has been recalculated to reflect the change, per the *2006 IPCC Guidelines* (IPCC 2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies. References for the data are provided for additional information.

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 2014. 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 molecular mass basis and on a Global Warming Potential (GWP) weighted basis¹ 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}

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...”⁴ The United States views this report as an opportunity to fulfill these commitments 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, 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 2003). 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

¹ More information provided in “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. See <<http://unfccc.int>>. (UNEP/WMO 2000)

⁴ Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12). Subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. See <<http://unfccc.int>>.

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 at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This report presents information in accordance with these guidelines.

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 and U.S. Territories.⁵ The structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2014).

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the gross emissions total presented in this report for the United States excludes emissions and sinks from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from LULUCF. All emissions and sinks are calculated using internationally-accepted methods provided by the IPCC.⁶ Additionally, the calculated emissions and sinks 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.⁷ The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. Emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather this inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the EPA’s GHGRP. 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO₂ underground for sequestration or other reasons.⁸ Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections in this report’s chapters, EPA is analyzing the data for use, as applicable, to improve the national estimates presented in this Inventory.

⁵ U.S. Territories include American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands.

⁶ See <<http://www.ipcc-nrgip.iges.or.jp/public/index.html>>.

⁷ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>>.

⁸ See <<http://www.epa.gov/climatechange/emissions/ghgrulemaking.html>> and <<http://ghgdata.epa.gov/ghgp/main.do>>.

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, deforestation, land-use changes, and other sources have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (NOAA 2014). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth and then re-radiate this energy with some returning to the Earth's surface, 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 in the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (EPA 2009). 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. But, as the concentrations of these gases continue to increase from man-made sources, the Earth's temperature is climbing above past levels. The Earth's averaged land and ocean surface temperature has increased by about 1.2 to 1.9 degrees Fahrenheit since 1880. The last three decades have each been the warmest decade successively at the Earth's surface since 1850 (IPCC 2013). Most of the warming in recent decades is very likely the result of human activities. Other aspects of the climate are also changing such as rainfall patterns, snow and ice cover, and sea level.

If greenhouse gases 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 (IPCC 2013). Scientists are certain that human activities are changing the composition of the atmosphere, and that increasing the concentration of greenhouse gases will change the planet's climate. However, they are not sure by how much it will change, at what rate it will change, or what the exact effects will be.⁹

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). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the space and the earth system.¹⁰ A gauge of these changes is called radiative forcing, which is a measure of the influence a perturbation has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system (IPCC 2013). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

Human activities are continuing to affect the Earth's energy budget by changing the emissions and resulting atmospheric concentrations of radiatively important gases and aerosols and by changing land surface properties (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

⁹ For more information see <<http://www.epa.gov/climatechange/science>>.

¹⁰ For more on the science of climate change, see NRC (2012).

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.¹¹ 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. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) O_3 . Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) 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 affecting the radiative forcing of clouds and precipitation 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, 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	401 ppm ^a	1.823 ppm ^b	0.327 ppm ^b	8.3 ppt ^b	79 ppt ^c
Rate of concentration change	2.3 ppm/yr	5 ppb/yr ^{d,e}	0.8 ppb/yr ^e	0.27 ppt/yr ^e	0.7 ppt/yr ^e
Atmospheric lifetime (years)	See footnote ^f	12.4 ^g	121 ^g	3,200	50,000

^a The atmospheric CO_2 concentration is the 2015 annual average at the Mauna Loa, HI station (NOAA/ESRL 2016).

^b The values presented are global 2014 annual average mole fractions (CDIAC 2015).

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

^d The growth rate for atmospheric CH_4 decreased from over 10 ppb/yr in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 5 ppb/year.

^e The rate of concentration change is the average rate of change between 2005 and 2011 (IPCC 2013).

^f For a given amount of carbon dioxide 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.

^g 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 2011 through 2015 has fluctuated between 1.7 to 3.0 ppm per year over this period (NOAA/ESRL 2016).

¹¹ Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

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, this has been determined to have a negligible effect on 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 contrails, which consist of water vapor and other substances, are aviation-induced clouds with the same radiative forcing effects as high-altitude cirrus clouds (IPCC 1999).

Carbon Dioxide (CO_2). 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 401 ppmv in 2015, a 43 percent increase (IPCC 2013 and NOAA/ESRL 2016).^{12,13} 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 (CH_4). 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. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 160 percent since 1750, from a pre-industrial value of about 700 ppb to 1,823 ppb in 2014,¹⁴ although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to about 5 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 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 (N_2O). 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

¹² The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2013).

¹³ 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).

¹⁴ This value is the global 2014 annual average mole fraction (CDIAC 2015).

treatment and waste incineration; and biomass burning. The atmospheric concentration of N₂O has increased by 21 percent since 1750, from a pre-industrial value of about 270 ppb to 327 ppb in 2014,¹⁵ a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2007).

Ozone (O₃). Ozone is present in both the upper stratosphere,¹⁶ where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,¹⁷ 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 was expected to reach a maximum in about 2000 before starting to recover.

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 CO₂, black carbon, and CH₄. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds (including CH₄) 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, Perfluorocarbons, Sulfur Hexafluoride, and Nitrogen Trifluoride. Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. 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 CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is an important greenhouse gas in addition to shielding 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 5¹⁸ countries beginning in 1996, and then followed by 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 of this report for informational purposes.

Hydrofluorocarbons, PFCs, SF₆, and NF₃ are not ozone depleting substances, and therefore are not covered under the Montreal Protocol. They are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2013). Perfluorocarbons, SF₆, and NF₃ 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, SF₆, and NF₃ is also small, but they have a significant growth rate, 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).

¹⁵ This value is the global 2014 annual average (CDIAC 2015).

¹⁶ 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.

¹⁷ 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.

¹⁸ 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.

Carbon Monoxide. Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH₄ and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH₄ 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 CO₂. 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 NO₂) are indirect and result from their role in promoting the formation of ozone in the troposphere, are a precursor to nitrate particles (i.e., aerosols) and, to a lesser degree, lower stratosphere, where they have positive radiative forcing effects.¹⁹ Additionally, NO_x emissions are also likely to decrease CH₄ 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 N₂O. 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 and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous²⁰ aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning. 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 GHG forcing” (IPCC 2013).²¹ Although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.²² Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a 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.

¹⁹ NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

²⁰ Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2013).

²¹ The IPCC (2013) defines high confidence as an indication of strong scientific evidence and agreement in this statement.

²² 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).

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 ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (IPCC 2007). 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 CO₂, and therefore GWP-weighted emissions are measured in million metric tons of CO₂ equivalent (MMT CO₂ Eq.).²³ The relationship between kilotons (kt) of a gas and MMT CO₂ 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 CO₂ Eq. = Million metric tons of CO₂ 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...²⁴

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO₂, CH₄, N₂O, HFCs, PFCs, SF₆, NF₃) 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., SO₂ 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.

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

Gas	Atmospheric Lifetime	GWP ^c
CO ₂	b	1
CH ₄ ^a	12	25
N ₂ O	114	298
HFC-23	270	14,800
HFC-32	4.9	675

²³ Carbon comprises 12/44ths of carbon dioxide by weight.

²⁴ 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).

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
HFC-4310mee	15.9	1,640
CF ₄	50,000	7,390
C ₂ F ₆	10,000	12,200
C ₄ F ₁₀	2,600	8,860
C ₆ F ₁₄	3,200	9,300
SF ₆	3,200	22,800
NF ₃	740	17,200

^a The GWP of CH₄ 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 CO₂ is not included.

^b For a given amount of carbon dioxide 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 100-year time horizon.

Source: (IPCC 2007)

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

In 2014, the IPCC published its *Fifth Assessment Report* (AR5), which provided an updated and more comprehensive scientific assessment of climate change. Within the AR5 report, the GWP values of several 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 interesting to review the changes to the GWP values and the impact improved understanding has on the total GWP-weighted emissions of the United States. In the AR5, the IPCC has applied an improved calculation of CO₂ radiative forcing and an improved CO₂ 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.

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

Gas	SAR	AR4	AR5 ^a	AR5 with feedbacks ^b	Comparison to AR4		
					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 ₂ O	310	298	265	298	12	(33)	0
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-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)
HFC-4310mee	1,300	1,640	1,650	1,952	(340)	10	312
CF ₄	6,500	7,390	6,630	7,349	(890)	(760)	(41)
C ₂ F ₆	9,200	12,200	11,100	12,340	(3,000)	(1,100)	140
C ₄ F ₁₀	7,000	8,860	9,200	10,213	(1,860)	340	1,353
C ₆ F ₁₄	7,400	9,300	7,910	8,780	(1,900)	(1,390)	(520)
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

NC – No Change

NA – Not Applicable

^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-CO₂ gases in order to be consistent with the approach used in calculating the CO₂ lifetime.

Additionally, the AR5 reported separate values for fossil versus biogenic methane in order to account for the CO₂ oxidation product.

^c The GWP of CH₄ 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 CO₂ is only included in the value from AR5 that includes climate-carbon feedbacks.

Note: Parentheses indicate negative values.

Source: (IPCC 2013, IPCC 2007, IPCC 2001, IPCC 1996).

To comply 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.²⁵ 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.

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.

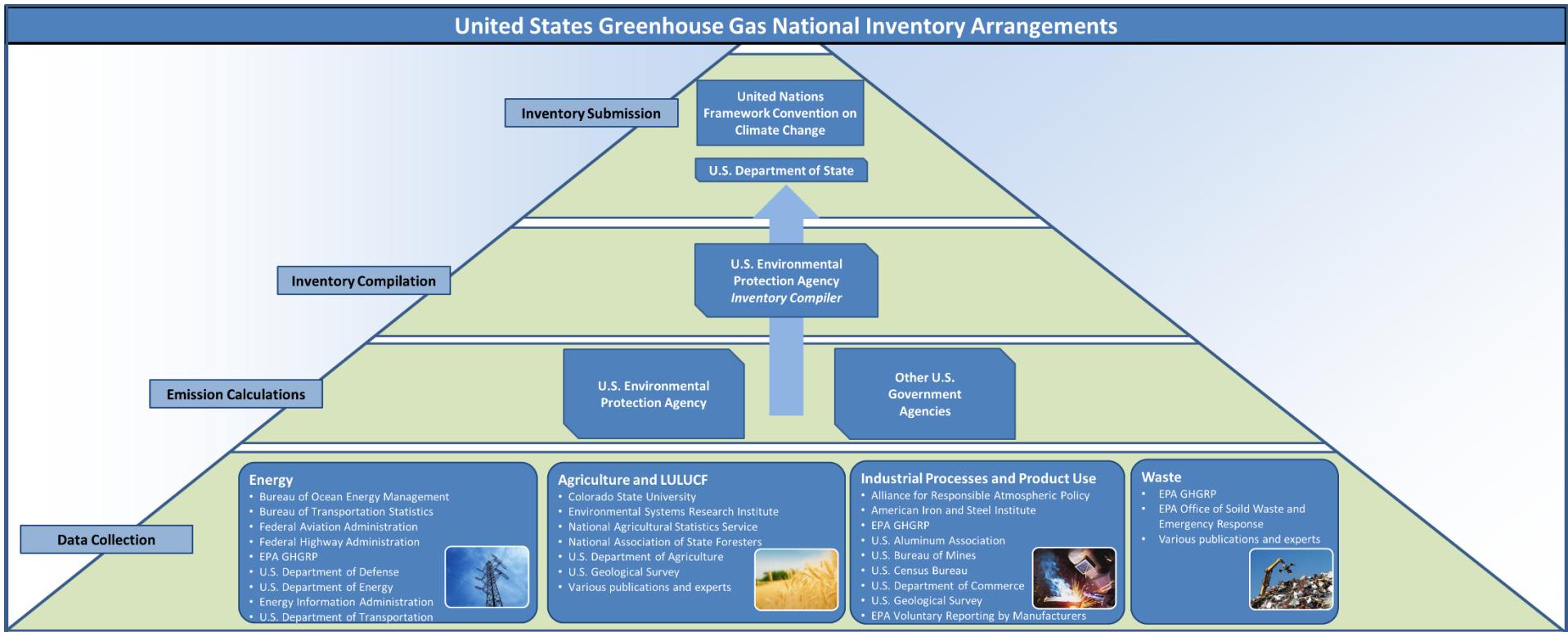
Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format tables. EPA's Office of Transportation and Air Quality (OTAQ) is also involved in calculating emissions for the Inventory. While the U.S. Department of State officially submits the annual Inventory to the UNFCCC, EPA's OAP serves as the Inventory focal point for technical questions and comments on the U.S. Inventory. The staff of OAP and OTAQ coordinates the annual methodological choice, activity data collection, and emission calculations at the individual source category level. Within OAP, an inventory coordinator compiles the entire Inventory into the proper reporting format for submission to the UNFCCC, and is responsible for the collection and consistency of cross-cutting issues in the Inventory.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the Inventory calculations. Formal relationships exist between EPA and other U.S. agencies that provide official data for use in the Inventory. The U.S. Department of Energy's Energy Information Administration provides

²⁵ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

national fuel consumption data and the U.S. Department of Defense provides military fuel consumption and bunker fuels. Informal relationships also exist with other U.S. agencies to provide activity data for use in EPA's emission calculations. These include: the U.S. Department of Agriculture, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, the National Agricultural Statistics Service, 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, the U.S. Department of State officially submits the Inventory to the UNFCCC each April. Figure 1-1 diagrams the National Inventory Arrangements.

Figure 1-1: National Inventory Arrangements Diagram



1.3 Inventory Process

EPA has a decentralized 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 is responsible for compiling all emission estimates and ensuring consistency and quality throughout the NIR and CRF tables. Emission calculations for individual sources are the responsibility of individual source leads, who are most familiar with each source category and the unique characteristics of its emissions profile. The individual source leads determine the most appropriate methodology and collect the best activity data to use in the emission calculations, based upon their expertise in the source category, as well as coordinating with researchers and contractors familiar with the sources. A multi-stage process for collecting information from the individual source leads and producing the Inventory is undertaken annually to compile all information and data.

Methodology Development, Data Collection, and Emissions and Sink Estimation

Source leads at EPA collect input data and, as necessary, evaluate or develop the estimation methodology for the individual source categories. For most source 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 category are being developed for the first time, or if the methodology is changing for an existing source category (e.g., the United States is implementing a higher Tiered approach for that source category), then the source category lead will develop a new methodology, gather the most appropriate activity data and emission factors (or in some cases direct emission measurements) for the entire time series, and conduct a special source-specific peer review process involving relevant experts from industry, government, and universities.

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

Summary Spreadsheet Compilation and Data Storage

The inventory coordinator at EPA collects the source categories’ descriptive text and Annexes, and also aggregates the emission estimates into a summary spreadsheet that links the individual source category spreadsheets together. This summary sheet 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 category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Recent Trends sections of the Inventory report. Electronic copies of each year’s summary spreadsheet, which contains 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.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source 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 Recent Trends sections 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 lead, which contain source emissions and activity data. The inventory coordinator integrates the source 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 and quality 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 source leads, are completed for the entire time series of CRF tables before submission.

QA/QC and Uncertainty

QA/QC and uncertainty analyses are supervised by the QA/QC and Uncertainty coordinators, who have general oversight over the implementation of the QA/QC plan and the overall uncertainty analysis for the Inventory (see sections on QA/QC and Uncertainty, below). These coordinators work closely with the source leads to ensure that a consistent QA/QC plan and uncertainty analysis is implemented across all inventory sources. The inventory QA/QC plan, detailed in a following section, is consistent with the quality assurance procedures outlined by EPA and IPCC.

Expert and Public Review Periods

During the Expert Review period, a first draft of the document is sent to a select list of technical experts outside of EPA. The purpose of the Expert Review is to 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, a second draft of the document is released for public review by publishing a notice in the U.S. Federal Register and posting the document on the EPA Web site. The Public Review period allows for a 30 day comment period and is open to the entire U.S. public.

Final Submittal to UNFCCC and Document Printing

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final National Inventory Report and the accompanying Common Reporting Format Reporter database. The U.S. Department of State sends the official submission of the U.S. Inventory to the UNFCCC. The document is then formatted and posted online, available for the public.¹

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 the extent possible, the present report relies on published activity and emission factor data. Depending on the emission

¹ See <<http://epa.gov/climatechange/ghgemissions/usinventoryreport.html>>

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.

The IPCC methodologies provided in the *2006 IPCC Guidelines* represent baseline 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. 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. Complete documentation is provided in the annexes on the detailed methodologies and data sources utilized in the calculation of each source category.

Box 1-3: IPCC Reference Approach

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO₂ emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. 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.

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."² By definition, key categories include those categories that have the greatest contribution to the absolute level of national emissions. In addition, when an entire time series of emission and removal estimates is prepared, a thorough investigation of key categories must also account for the influence of trends and uncertainties of individual source and sink categories. This analysis culls out source and sink categories that diverge from the overall trend in national emissions. Finally, a qualitative evaluation of key categories is performed to capture any categories that were not identified in any of the quantitative analyses.

Approach 1, as defined in the *2006 IPCC Guidelines* (IPCC 2006), was implemented to identify the key categories for the United States. 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. Following Approach 1, Approach 2, as defined in the *2006 IPCC Guidelines* (IPCC 2006), was then implemented to identify any additional key categories not already identified in Approach 1 assessment. This analysis, which includes each source category's uncertainty assessments (or proxies) in its calculations, was also performed twice to include or exclude LULUCF categories.

In addition to conducting Approach 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the *2006 IPCC Guidelines* (IPCC 2006), was conducted to capture any key categories that were not identified by either quantitative method. One additional key category, international bunker fuels, was identified using this qualitative assessment. International bunker fuels are fuels consumed for aviation or marine international transport activities, and emissions from these fuels are reported separately from totals in accordance

² See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006). See <<http://www.ipcc-ccip.iges.or.jp/public/2006gl/index.html>>.

with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to Approach 1. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key, because it would qualify bunker fuels as a key category according to Approach 2. Table 1-4 presents the key categories for the United States (including and excluding LULUCF categories) using emissions and uncertainty data in this report, and ranked according to their sector and global warming potential (GWP)-weighted emissions in 2014. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Approach 1, Approach 2, and/or qualitative assessments). Annex 1 of this report provides additional information regarding the key categories in the United States and the methodologies used to identify them.

Table 1-4: Key Categories for the United States (1990-2014)

IPCC Source Categories	Gas									Qual ^a	2014 Emissions (MMT CO ₂ Eq.)		
		Approach 1				Approach 2							
		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													
CO ₂ Emissions from Stationary Combustion - Coal - Electricity Generation	CO ₂	•	•	•	•	•	•	•	•		1,570.4		
CO ₂ Emissions from Mobile Combustion: Road	CO ₂	•	•	•	•	•	•	•	•		1,467.5		
CO ₂ Emissions from Stationary Combustion - Gas - Industrial	CO ₂	•	•	•	•	•		•			466.0		
CO ₂ Emissions from Stationary Combustion - Gas - Electricity Generation	CO ₂	•	•	•	•	•	•	•	•		443.2		
CO ₂ Emissions from Stationary Combustion - Gas - Residential	CO ₂	•	•	•	•	•		•			277.6		
CO ₂ Emissions from Stationary Combustion - Oil - Industrial	CO ₂	•	•	•	•	•	•	•	•		271.9		
CO ₂ Emissions from Stationary Combustion - Gas - Commercial	CO ₂	•	•	•	•	•	•	•			189.2		
CO ₂ Emissions from Mobile Combustion: Aviation	CO ₂	•	•	•	•	•	•	•			150.1		
CO ₂ Emissions from Non-Energy Use of Fuels	CO ₂	•	•	•	•	•	•	•	•		114.3		
CO ₂ Emissions from Mobile Combustion: Other	CO ₂	•	•	•	•						92.0		
CO ₂ Emissions from Stationary Combustion - Coal - Industrial	CO ₂	•	•	•	•	•	•	•	•		75.3		
CO ₂ Emissions from Stationary Combustion - Oil - Residential	CO ₂	•	•	•	•						67.5		
CO ₂ Emissions from Natural Gas Systems	CO ₂	•		•		•		•			42.4		

CO ₂ Emissions from Stationary Combustion - Oil - Commercial	CO ₂	• • • •					38.2
CO ₂ Emissions from Stationary Combustion - Oil - U.S. Territories	CO ₂	• • • •					34.6
CO ₂ Emissions from Mobile Combustion: Marine	CO ₂	• • • •					28.0
CO ₂ Emissions from Stationary Combustion - Oil - Electricity Generation	CO ₂	• • • •		•	•		25.3
CO ₂ Emissions from Stationary Combustion - Coal - Commercial	CO ₂		• •				4.5
CO ₂ Emissions from Stationary Combustion - Gas - U.S. Territories	CO ₂				•		3.0
CO ₂ Emissions from Stationary Combustion - Coal - Residential	CO ₂				•		0.0
CH ₄ Emissions from Natural Gas Systems	CH ₄	• • • •	• • • •	•	•		176.1
CH ₄ Emissions from Petroleum Systems	CH ₄	• • • •	• •	• •	• •		68.1
Fugitive Emissions from Coal Mining	CH ₄	• • • •	• •	• •	• •		67.6
Non-CO ₂ Emissions from Stationary Combustion - Residential	CH ₄			•	•		5.0
Non-CO ₂ Emissions from Stationary Combustion - Electricity Generation	N ₂ O		• •	• •	• •	•	19.6
N ₂ O Emissions from Mobile Combustion: Road	N ₂ O	• • • •	• •	• •	•		12.5
International Bunker Fuels ^b	Several					•	104.2

Industrial Processes and Product Use

CO ₂ Emissions from Iron and Steel Production & Metallurgical Coke Production	CO ₂	• • • •	• • • •	•	•		55.4
CO ₂ Emissions from Cement Production	CO ₂	•		•			38.8
CO ₂ Emissions from Other Process Uses of Carbonates	CO ₂		•	•			12.1
N ₂ O Emissions from Adipic Acid Production	N ₂ O	•		•			5.4
Emissions from Substitutes for Ozone Depleting Substances	HiGWP	• • • •	• • • •	•	•		161.2
SF ₆ Emissions from Electrical Transmission and Distribution	HiGWP		•	•	•	•	5.6
HFC-23 Emissions from HCFC-22 Production	HiGWP	• • • •		•			5.0
PFC Emissions from Aluminum Production	HiGWP		•	•			2.5

Agriculture							
CH ₄ Emissions from Enteric Fermentation	CH ₄	•	•	•	•	•	164.3
CH ₄ Emissions from Manure Management	CH ₄	•	•	•	•	•	61.2
Direct N ₂ O Emissions from Agricultural Soil Management	N ₂ O	•		•	•	•	261.0
Indirect N ₂ O Emissions from Applied Nitrogen	N ₂ O	•		•	•	•	57.3
Waste							
CH ₄ Emissions from Landfills	CH ₄	•	•	•	•	•	148.0
Land Use, Land-Use Change, and Forestry							
CO ₂ Emissions from Land Converted to Grassland	CO ₂			•			40.4
CO ₂ Emissions from Land Converted to Cropland	CO ₂			•	•	•	22.1
CO ₂ Emissions from Grassland Remaining Grassland	CO ₂			•		•	3.8
CO ₂ Emissions from Cropland Remaining Cropland	CO ₂			•	•	•	(8.4)
CO ₂ Emissions from Landfilled Yard Trimmings and Food Scraps	CO ₂			•		•	(11.6)
CO ₂ Emissions from Urban Trees	CO ₂			•	•	•	(90.6)
CO ₂ Emissions from Forest Land Remaining Forest Land	CO ₂			•	•	•	(742.3)
CH ₄ Emissions from Forest Fires	CH ₄					•	7.3
Subtotal Without LULUCF							6,687.8
Total Emissions Without LULUCF							6,870.5
Percent of Total Without LULUCF							97%
Subtotal With LULUCF							5,905.5
Total Emissions With LULUCF							6,108.0
Percent of Total With LULUCF							97%

^a Qualitative criteria.

^b Emissions from this source not included in totals.

Note: Parentheses indicate negative values (or sequestration).

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:

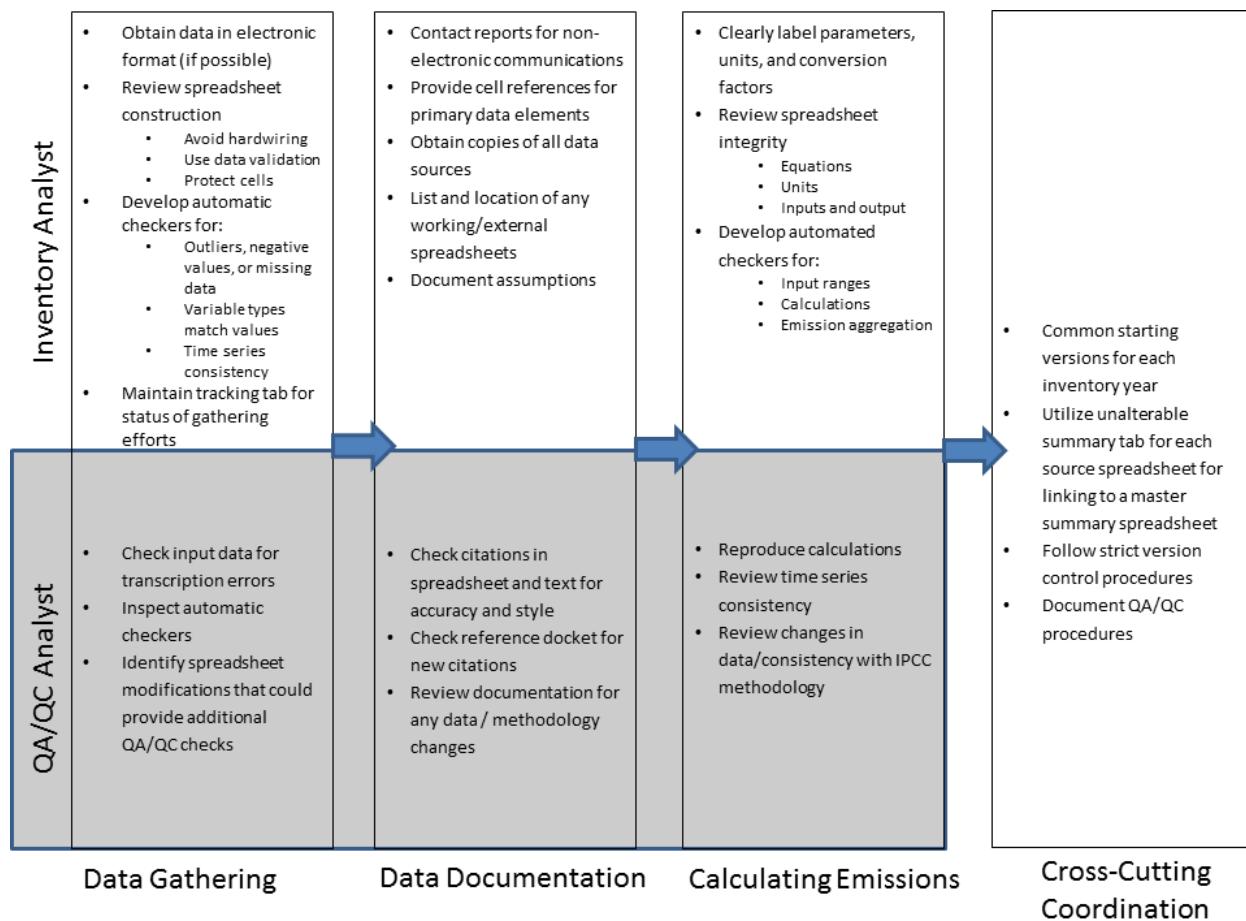
- *Procedures and Forms*: detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures*: application of QA/QC procedures throughout the whole inventory development process from initial data collection, through preparation of the emission estimates, to publication of the Inventory
- *Quality Assurance*: 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)
- *Quality Control*: consideration of secondary data and source-specific checks (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
- *Tier 1 (general) and Tier 2 (source-specific) Checks*: quality controls and checks, as recommended by *IPCC Good Practice Guidance*
- *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
- *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.

In addition, based on the national QA/QC plan for the Inventory, source-specific QA/QC plans have been developed for a number of sources. These plans follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific text and spreadsheets of the individual sources. For each greenhouse gas emissions source or sink included in this Inventory, a minimum of a Tier 1 QA/QC analysis has been undertaken. Where QA/QC activities for a particular source go beyond the minimum Tier 1 level, further explanation is provided within the respective source category text.

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 at two stages—an expert review and a public review. While both phases can significantly contribute to 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 estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

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



1.7 Uncertainty Analysis of Emission Estimates

Uncertainty estimates are an essential element of a complete and transparent emissions inventory. Uncertainty information is not intended to dispute the validity of the inventory estimates, but to help prioritize efforts to improve the accuracy of future inventories and guide future decisions on methodological choice. While the U.S. Inventory calculates its emission estimates with the highest possible accuracy, uncertainties are associated to a varying degree with the development of emission estimates for any inventory. Some of the current estimates, such as those for carbon dioxide (CO₂) emissions from energy-related activities, are considered to have minimal uncertainty associated with them. For some other categories of emissions, however, a lack of data or an incomplete understanding of how emissions are generated increases the uncertainty surrounding the estimates presented. The UNFCCC reporting guidelines follow the recommendation in the *2006 IPCC Guidelines* (IPCC 2006) and require that countries provide single point estimates for each gas and emission or removal source category. Within the discussion of each emission source, specific factors affecting the uncertainty associated with the estimates are discussed.

Additional research in the following areas could help reduce uncertainty in the U.S. Inventory:

- *Incorporating excluded emission sources.* Quantitative estimates for some of the sources and sinks of greenhouse gas emissions are not available at this time. In particular, emissions from some land-use activities and industrial processes are not included in the inventory either because data are incomplete or

because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report.

- *Improving the accuracy of emission factors.* Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to CH₄ and N₂O emissions from stationary and mobile combustion is highly uncertain.
- *Collecting detailed activity data.* Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of SF₆ from electrical transmission and distribution is limited due to a lack of activity data regarding national SF₆ consumption or average equipment leak rates.

The overall uncertainty estimate for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology. Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions are shown below, in Table 1-5.

The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for individual source categories. Approach 2 uncertainty analysis, employing the Monte Carlo Stochastic Simulation technique, was applied wherever data and resources permitted; further explanation is provided within the respective source category text and in Annex 7. Consistent with the *2006 IPCC Guidelines* (IPCC 2006), over a multi-year timeframe, the United States expects to continue to improve the uncertainty estimates presented in this report.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty (MMT CO₂ Eq. and Percent)

Gas	2014 Emission Estimate ^a (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^b				Mean ^c (MMT CO ₂ Eq.)	Standard Deviation ^c (MMT CO ₂ Eq.)		
		(MMT CO ₂ Eq.)		(%)					
		Lower Bound ^d	Upper Bound ^d	Lower Bound	Upper Bound				
CO ₂	5,555.6	5,459.4	5,830.0	-2%	5%	5,643.8	94.9		
CH ₄ ^e	730.8	674.3	917.5	-8%	26%	785.0	60.2		
N ₂ O ^e	403.5	322.5	447.9	-20%	11%	378.6	32.2		
PFC, HFC, SF ₆ , and NF ₃ ^e	175.3	172.3	190.9	-4%	6%	181.6	4.7		
Total	6,865.2	6,765.4	7,223.9	-2%	5%	6,989.0	117.5		
LULUCF Emissions^f	24.6	12.8	38.9	-48%	58%	23.0	6.8		
LULUCF Total Net Flux^g	(787.0)	(1,051.4)	(647.8)	-18%	34%	(847.2)	102.9		
LULUCF Sector Total^h	(762.5)	(1,029.8)	(622.5)	-18%	35%	(824.2)	103.0		
Net Emissions (Sources and Sinks)	6,102.7	5,861.6	6,477.6	-4%	6%	6,164.8	156.7		

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) is presented without LULUCF. Net emissions is presented with LULUCF.

^a Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported in this table exclude approximately 5.3 MMT CO₂ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory.

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

^c 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.

^d 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.

^e The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH₄, N₂O and high GWP gases used in the inventory emission calculations for 2014.

^f LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Agricultural Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^g Net CO₂ flux 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, Settlements Remaining Settlements, and Other.

^h The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Emissions calculated for the U.S. Inventory reflect current best estimates; in some cases, however, estimates are based on approximate methodologies, assumptions, and incomplete data. As new information becomes available in the future, the United States will continue to improve and revise its emission estimates. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the emission estimates and for a more detailed discussion of the limitations of the current analysis and plans for improvement. Annex 7 also includes details on the uncertainty analysis performed for selected source categories.

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 2014. Although this report is intended to be comprehensive, certain sources have been identified which were excluded from the estimates presented for various reasons. Generally speaking, sources not accounted for in this Inventory are excluded due to data limitations or a lack of thorough understanding of the emission process. The United States is continually working to improve upon the understanding of such sources and seeking to find the data required to estimate related emissions. As such improvements are implemented, new emission sources are quantified and included in the Inventory. For a complete list of sources not included, see Annex 5 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 segregated into five sector-specific chapters, listed below in Table 1-6. In addition, chapters on Trends in Greenhouse Gas Emissions and Other information to be considered as part of the U.S. Inventory submission are included.

Table 1-6: 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	Anthropogenic 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 , CH ₄ , and N ₂ O from forest management, other land-use activities, and land-use change.
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 emission trends for each IPCC defined sector

Source category: Description of source pathway and emission trends.

Methodology: Description of analytical methods employed to produce emission estimates and identification of data references, primarily for activity data and emission factors.

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

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

Recalculations: 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 source-specific planned improvements, if applicable.

Special attention is given to CO₂ 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 1-7.

Table 1-7: 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 ₂ O, and Indirect Greenhouse Gases from Stationary Combustion
3.2. Methodology for Estimating Emissions of CH ₄ , N ₂ O, 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 ₂ O 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 ₂ O Emissions from Manure Management
3.12. Methodology for Estimating N ₂ O 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. Planned Improvements
- ANNEX 8 QA/QC Procedures
- 8.1. Background
 - 8.2. Purpose
 - 8.3. Assessment Factors

2. Trends in Greenhouse Gas Emissions

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

In 2014, total U.S. greenhouse gas emissions were 6,870.5 MMT or million metric tons carbon dioxide (CO₂) Eq. Total U.S. emissions have increased by 7.4 percent from 1990 to 2014, and emissions increased from 2013 to 2014 by 1.0 percent (70.5 MMT CO₂ Eq.). The increase in CO₂ emissions from fossil fuel combustion was a result of multiple factors, including: (1) colder winter conditions in the first quarter of 2014 resulting in an increased demand for heating fuel in the residential and commercial sectors; (2) an increase in transportation emissions resulting from an increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes; and (3) an increase in industrial production across multiple sectors resulting in slight increases in industrial sector emissions. Since 1990, U.S. emissions have increased at an average annual rate of 0.3 percent. Figure 2-1 through Figure 2-3 illustrate the overall trend in total U.S. emissions by gas, annual changes, and absolute changes since 1990. Overall, net emissions in 2014 were 8.6 percent below 2005 levels as shown in Table 2-1.

Figure 2-1: U.S. Greenhouse Gas Emissions by Gas (MMT CO₂ Eq.)

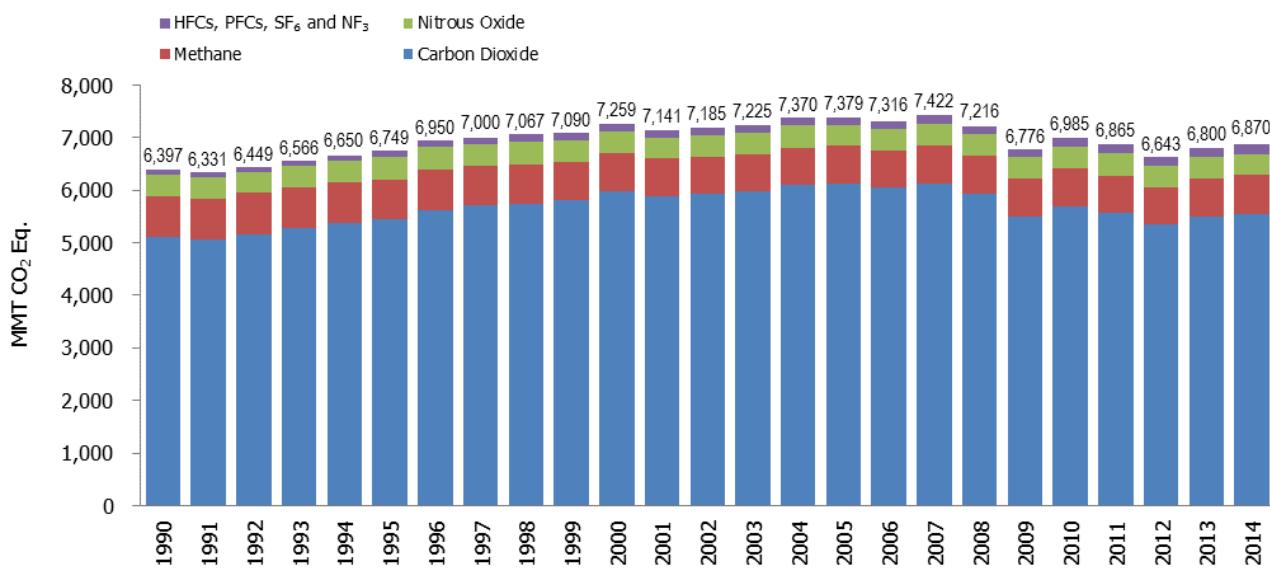


Figure 2-2: Annual Percent Change in U.S. Greenhouse Gas Emissions Relative to the Previous Year

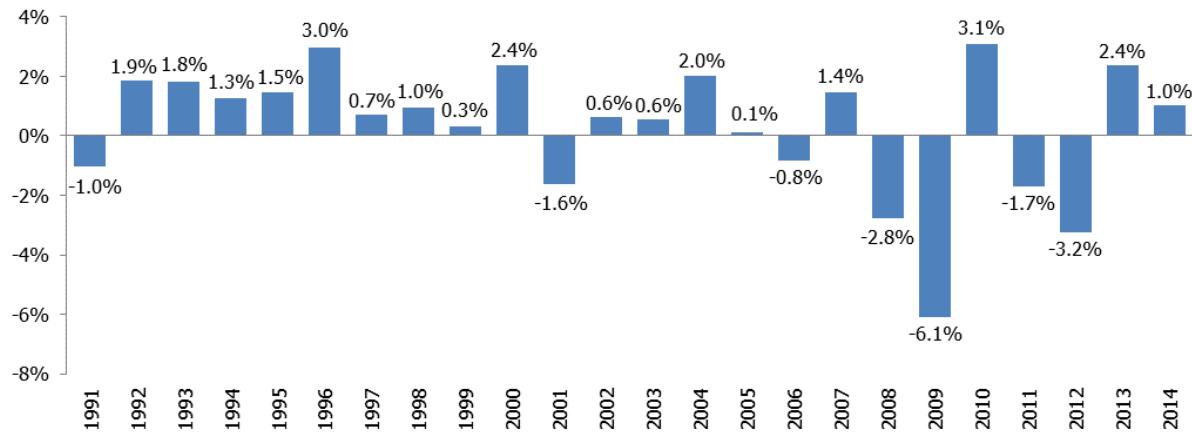
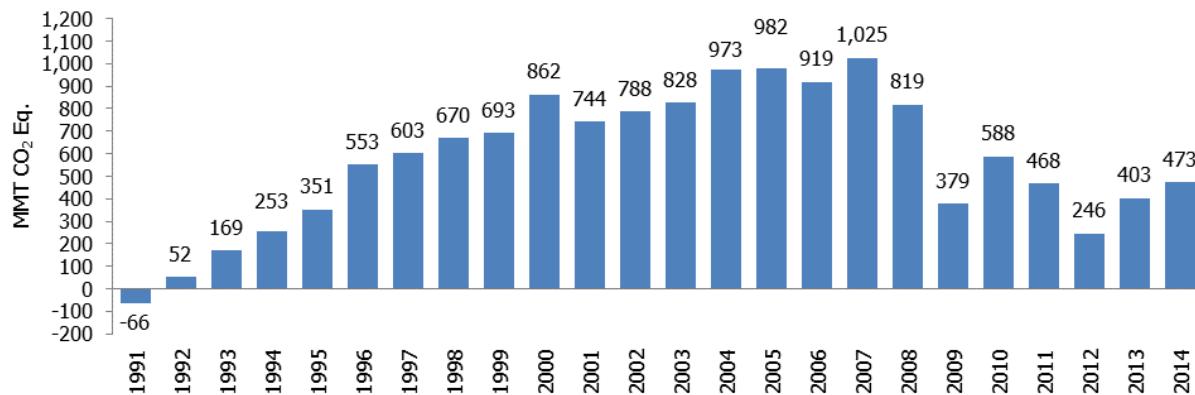


Figure 2-3: Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990 (1990=0, MMT CO₂ Eq.)



Overall, from 1990 to 2014, total emissions of CO₂ increased by 440.9 MMT CO₂ Eq. (8.6 percent), while total emissions of methane (CH₄) decreased by 43.0 MMT CO₂ Eq. (5.6 percent), and total emissions of nitrous oxide (N₂O) decreased by 2.7 MMT CO₂ Eq. (0.7 percent). During the same period, aggregate weighted emissions of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), and nitrogen trifluoride (NF₃) rose by 78.1 MMT CO₂ Eq. (76.6 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF₆, and NF₃ are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF₆, and NF₃, 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, and landfilled yard trimmings. These were estimated to offset 11.5 percent of total emissions in 2014.

As the largest contributor to U.S. greenhouse gas emissions, CO₂ from fossil fuel combustion has accounted for approximately 76 percent of GWP-weighted emissions for the entire time series since 1990, from 74 percent of total GWP-weighted emissions in 1990 to 76 percent in 2014. Emissions from this source category grew by 9.9 percent (467.5 MMT CO₂ Eq.) from 1990 to 2014 and were responsible for most of the increase in national emissions during this period. From 2013 to 2014, these emissions increased by 1.0 percent (50.6 MMT CO₂ Eq.). Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO₂ emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, energy fuel choices,

and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States fluctuates primarily 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 in a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants.

In the longer term, energy consumption patterns respond to changes that affect the scale of consumption (e.g., population, number of cars, and size of houses), the efficiency with which energy is used in equipment (e.g., cars, power plants, steel mills, and light bulbs), and behavioral choices (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related CO₂ emissions also depend on the type of fuel or energy consumed and its C intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO₂ emissions because of the lower C content of natural gas.

A brief discussion of the year to year variability in fuel combustion emissions is provided below, beginning with 2010.

From 2010 to 2011, CO₂ emissions from fossil fuel combustion decreased by 2.4 percent. This decrease is a result of multiple factors including: (1) a decrease in the C intensity of fuels consumed to generate electricity due to a decrease in coal consumption, with increased natural gas consumption and a significant increase in hydropower used; (2) a decrease in transportation-related energy consumption due to higher fuel costs, improvements in fuel efficiency, and a reduction in miles traveled; and (3) relatively mild winter conditions resulting in an overall decrease in energy demand in most sectors. Changing fuel prices played a role in the decreasing emissions. A significant increase in the price of motor gasoline in the transportation sector was a major factor leading to a decrease in energy consumption by 1.2 percent. In addition, an increase in the price of coal and a concurrent decrease in natural gas prices led to a 5.7 percent decrease and a 2.5 percent increase in fuel consumption of these fuels by electric generators. This change in fuel prices also reduced the carbon intensity of fuels used to produce electricity in 2011, further contributing to the decrease in fossil fuel combustion emissions.

From 2011 to 2012, CO₂ emissions from fossil fuel combustion decreased by 3.9 percent, with emissions from fossil fuel combustion at their lowest level since 1994. This decrease from 2011 to 2012 is primarily a result of the decrease in the carbon intensity of fuels used to generate electricity due to a slight increase in the price of coal, and a significant decrease in the price of natural gas. The consumption of coal used to generate electricity decreased by 12.3 percent, while consumption of natural gas for electricity generation increased by 20.4 percent. Also, emissions declined in the transportation sector largely due to a small increase in fuel efficiency across different transportation modes and limited new demand for passenger transportation. In 2012, weather conditions remained fairly constant in the summer and were much warmer in the winter compared to 2011, as cooling degree days increased by 1.7 percent while heating degree days decreased 12.6 percent. This decrease in heating degree days resulted in a decreased demand for heating fuel in the residential and commercial sector, which had a decrease in natural gas consumption of 11.7 and 8.0 percent, respectively.

From 2012 to 2013, CO₂ emissions from fossil fuel combustion increased by 2.6 percent. This increase is primarily a result of the increased energy consumption in the residential and commercial sectors, as heating degree days increased 18.5 percent in 2013 as compared to 2012. The cooler weather led to an increase of 17.1 and 12.9 percent direct use of fuels in the residential and commercial sectors, respectively. In addition, there was an increase of 1.5 and 0.8 percent in electricity consumption in the residential and commercial sectors, respectively, due to regions that heat their homes with electricity. The consumption of natural gas used to generate electricity decreased by 9.8 percent due to an increase in the price of natural gas. Electric power plants shifted some consumption from natural gas to coal, and as a result increased coal consumption to generate electricity by 4.0 percent. Lastly, industrial production increased 1.9 percent from 2012 to 2013, resulting in an increase in the in CO₂ emissions from fossil fuel combustion from the industrial sector by 3.7 percent.

From 2013 to 2014, CO₂ emissions from fossil fuel combustion increased by 1.0 percent. This increase is primarily a result of the increased energy consumption in the transportation (around 50 percent of increase), residential (around 30 percent of increase), and commercial (around 20 percent of increase) sectors. In the transportation sector, VMT increased by 1.3 percent resulting in increased fuel consumption across on-road transportation modes. Heating

degree days increased 1.9 percent in 2014 as compared to 2013, resulting in an increased demand in heating fuels for the residential and commercial sectors. The cooler weather led to an increase of 4.5 and 5.0 percent in direct use of fuels in the residential and commercial sectors, respectively. In addition, there was an increase of 0.9 and 1.1 percent in electricity consumption in the residential and commercial sectors, respectively, due to regions that heat their homes with electricity. There was also an increase in transportation emissions resulting from an increase in VMT and fuel use across on-road transportation modes in 2014. Lastly, industrial production increased 3.7 percent from 2013 to 2014, resulting in a slight increase in CO₂ emissions from fossil fuel combustion from the industrial sector by 0.1 percent. From the perspective of how these sector trends contributed to the overall 1.0 percent increase from 2013 to 2014, the residential and commercial sectors were approximately 37 percent of the annual increase, the transportation sector was 35 percent of the annual increase, and the industrial sector was just over 1 percent of the 2013 to 2014 increase in overall U.S. emissions.

Table 2-1 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of MMT CO₂ 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 CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	5,115.1	6,122.7	5,688.8	5,559.5	5,349.2	5,502.6	5,556.0
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
<i>Electricity Generation</i>	<i>1,820.8</i>	<i>2,400.9</i>	<i>2,258.4</i>	<i>2,157.7</i>	<i>2,022.2</i>	<i>2,038.1</i>	<i>2,039.3</i>
<i>Transportation</i>	<i>1,493.8</i>	<i>1,887.0</i>	<i>1,728.3</i>	<i>1,707.6</i>	<i>1,696.8</i>	<i>1,713.0</i>	<i>1,737.6</i>
<i>Industrial</i>	<i>842.5</i>	<i>828.0</i>	<i>775.5</i>	<i>773.3</i>	<i>782.9</i>	<i>812.2</i>	<i>813.3</i>
<i>Residential</i>	<i>338.3</i>	<i>357.8</i>	<i>334.6</i>	<i>326.8</i>	<i>282.5</i>	<i>329.7</i>	<i>345.1</i>
<i>Commercial</i>	<i>217.4</i>	<i>223.5</i>	<i>220.1</i>	<i>220.7</i>	<i>196.7</i>	<i>221.0</i>	<i>231.9</i>
<i>U.S. Territories</i>	<i>27.9</i>	<i>49.9</i>	<i>41.4</i>	<i>41.5</i>	<i>43.6</i>	<i>43.5</i>	<i>41.0</i>
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Iron and Steel Production &							
Metallurgical Coke Production	99.7	66.5	55.7	59.9	54.2	52.2	55.4
Natural Gas Systems	37.7	30.1	32.4	35.7	35.2	38.5	42.4
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.6	27.4	27.2	26.3	26.5	26.4	26.5
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Incineration of Waste	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Petroleum Systems	3.6	3.9	4.2	4.2	3.9	3.7	3.6
Aluminum Production	6.8	4.1	2.7	3.3	3.4	3.3	2.8
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	+	+	+	+	+	+	+
<i>Wood Biomass and Ethanol</i>							
<i>Consumption^a</i>	<i>219.4</i>	<i>229.8</i>	<i>265.1</i>	<i>268.1</i>	<i>267.7</i>	<i>286.3</i>	<i>293.7</i>
<i>International Bunker Fuels^b</i>	<i>103.5</i>	<i>113.1</i>	<i>117.0</i>	<i>111.7</i>	<i>105.8</i>	<i>99.8</i>	<i>103.2</i>
CH₄	773.9	717.4	722.4	717.4	714.4	721.5	730.8
Natural Gas Systems	206.8	177.3	166.2	170.1	172.6	175.6	176.1
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3

Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Petroleum Systems	38.7	48.8	54.1	56.3	58.4	64.7	68.1
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Wastewater Treatment	15.7	15.9	15.5	15.3	15.0	14.8	14.7
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Stationary Combustion	8.5	7.4	7.1	7.1	6.6	8.0	8.1
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3
Composting	0.4	1.9	1.8	1.9	1.9	2.0	2.1
Mobile Combustion	5.6	2.7	2.3	2.2	2.2	2.1	2.0
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Petrochemical Production	0.2	0.1	+	+	0.1	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
<i>International Bunker Fuels^b</i>	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N₂O	406.2	397.6	410.3	416.5	409.3	403.4	403.5
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Stationary Combustion	11.9	20.2	22.2	21.3	21.4	22.9	23.4
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Mobile Combustion	41.2	34.4	23.6	22.4	20.0	18.2	16.3
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4
Wastewater Treatment	3.4	4.3	4.5	4.7	4.8	4.8	4.8
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Composting	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Semiconductor Manufacture	+	0.1	0.1	0.2	0.2	0.2	0.2
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
<i>International Bunker Fuels^b</i>	0.9	1.0	1.0	1.0	0.9	0.9	0.9
HFCs	46.6	119.9	149.4	154.3	155.9	158.9	166.7
Substitution of Ozone Depleting Substances ^c	0.3	99.7	141.2	145.3	150.2	154.6	161.2
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Magnesium Production and Processing	0.0	0.0	+	+	+	0.1	0.1
PFCs	24.3	6.7	4.5	7.0	6.0	5.8	5.6
Semiconductor Manufacture	2.8	3.2	2.7	3.5	3.1	2.9	3.0
Aluminum Production	21.5	3.4	1.9	3.5	2.9	3.0	2.5
SF₆	31.1	14.0	9.5	10.0	7.6	7.2	7.3
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.6	1.5	1.0
Semiconductor Manufacture	0.5	0.7	0.4	0.4	0.4	0.4	0.7
NF₃	+	0.5	0.6	0.7	0.6	0.6	0.5
Semiconductor Manufacture	+	0.5	0.6	0.7	0.6	0.6	0.5
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
LULUCF Emissions^d	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^e	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^f	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Emissions from Wood Biomass and Ethanol 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 Small amounts of PFC emissions also result from this source.

^d LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Agricultural Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^e Net CO₂ flux 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, Settlements Remaining Settlements, and Other*. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

^f The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

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

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	5,115,095	6,122,747	5,688,756	5,559,508	5,349,221	5,502,551	5,556,007
Fossil Fuel Combustion	4,740,671	5,747,142	5,358,292	5,227,690	5,024,685	5,157,583	5,208,207
Electricity Generation	1,820,818	2,400,874	2,258,399	2,157,688	2,022,181	2,038,122	2,039,321
Transportation	1,493,758	1,887,033	1,728,267	1,707,631	1,696,752	1,713,008	1,737,598
Industrial	842,473	827,999	775,535	773,312	782,929	812,221	813,274
Residential	338,347	357,834	334,587	326,808	282,540	329,674	345,105
Commercial	217,393	223,480	220,125	220,749	196,714	221,030	231,917
U.S. Territories	27,882	49,923	41,379	41,503	43,569	43,528	40,991
Non-Energy Use of Fuels	118,114	138,876	114,063	108,515	105,624	121,682	114,311
Iron and Steel Production & Metallurgical Coke							
Production	99,669	66,543	55,671	59,928	54,229	52,201	55,355
Natural Gas Systems	37,732	30,076	32,439	35,662	35,203	38,457	42,351
Cement Production	33,278	45,910	31,256	32,010	35,051	36,146	38,755
Petrochemical Production	21,609	27,380	27,246	26,326	26,464	26,437	26,509
Lime Production	11,700	14,552	13,381	13,981	13,715	14,045	14,125
Other Process Uses of Carbonates	4,907	6,339	9,560	9,335	8,022	10,414	12,077
Ammonia Production	13,047	9,196	9,188	9,292	9,377	9,962	9,436
Incineration of Waste	7,972	12,454	11,026	10,550	10,362	9,421	9,421
Carbon Dioxide Consumption	1,472	1,375	4,425	4,083	4,019	4,188	4,471
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,730	4,029	4,449	4,179	4,007
Petroleum Systems	3,553	3,927	4,154	4,192	3,876	3,693	3,567
Aluminum Production	6,831	4,142	2,722	3,292	3,439	3,255	2,833
Soda Ash Production and Consumption	2,822	2,960	2,697	2,712	2,763	2,804	2,827
Ferroalloy Production	2,152	1,392	1,663	1,735	1,903	1,785	1,914
Titanium Dioxide Production	1,195	1,755	1,769	1,729	1,528	1,715	1,755
Glass Production	1,535	1,928	1,481	1,299	1,248	1,317	1,341
Phosphoric Acid Production	1,529	1,342	1,087	1,151	1,093	1,119	1,095
Zinc Production	632	1,030	1,182	1,286	1,486	1,429	956
Lead Production	516	553	542	538	527	546	518
Silicon Carbide Production and Consumption	375	219	181	170	158	169	173
Magnesium Production and Processing	1	3	1	3	2	2	2

Wood Biomass and Ethanol							
Consumption ^a	219,413	229,844	265,110	268,064	267,730	286,323	293,729
International Bunker Fuels ^b	103,463	113,139	116,992	111,660	105,805	99,763	103,201
CH₄	30,954	28,694	28,896	28,697	28,576	28,859	29,233
Natural Gas Systems	8,270	7,093	6,647	6,803	6,906	7,023	7,045
Enteric Fermentation	6,566	6,755	6,853	6,757	6,670	6,619	6,572
Landfills	7,182	6,161	5,685	5,774	5,691	5,772	5,919
Petroleum Systems	1,550	1,953	2,163	2,251	2,335	2,588	2,726
Coal Mining	3,860	2,565	3,293	2,849	2,658	2,584	2,703
Manure Management	1,486	2,254	2,437	2,460	2,548	2,455	2,447
Wastewater Treatment	626	636	618	610	601	592	588
Rice Cultivation	525	521	474	474	476	477	476
Stationary Combustion	339	296	283	283	265	320	324
Abandoned Underground Coal Mines	288	264	263	257	249	249	253
Composting	15	75	73	75	77	81	82
Mobile Combustion	226	110	91	90	86	84	82
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
Petrochemical Production	9	3	2	2	3	3	5
Ferroalloy Production	1	+	+	+	1	+	1
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels ^b	7	5	6	5	4	3	3
N₂O	1,363	1,334	1,377	1,398	1,373	1,354	1,354
Agricultural Soil Management	1,018	997	1,076	1,084	1,084	1,069	1,068
Stationary Combustion	40	68	74	71	72	77	79
Manure Management	47	55	58	58	59	59	59
Mobile Combustion	138	115	79	75	67	61	55
Nitric Acid Production	41	38	39	37	35	36	37
Adipic Acid Production	51	24	14	34	19	13	18
Wastewater Treatment	11	15	15	16	16	16	16
N ₂ O from Product Uses	14	14	14	14	14	14	14
Composting	1	6	5	6	6	6	6
Incineration of Waste	2	1	1	1	1	1	1
Semiconductor Manufacture	+	+	+	1	1	1	1
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
International Bunker Fuels ^b	3	3	3	3	3	3	3
HFCs	M						
Substitution of Ozone Depleting Substances ^c	M	M	M	M	M	M	M
HCFC-22 Production	3	1	1	1	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+
PFCs	M						
Semiconductor Manufacture	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
SF₆	1	1	+	+	+	+	+
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+

Semiconductor Manufacture	+		+	+	+	+	+	+
NF ₃	+		+	+	+	+	+	+
Semiconductor Manufacture	+		+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M - Mixture of multiple gases

^a Emissions from Wood Biomass and Ethanol Consumption are not included in totals.

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

^c Small amounts of PFC emissions also result from this source.

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

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 twenty-five-year period of 1990 to 2014, total emissions in the Energy, Industrial Processes and Product Use, and Agriculture sectors grew by 421.3 MMT CO₂ Eq. (7.9 percent), 38.3 MMT CO₂ Eq. (11.2 percent), and 41.6 MMT CO₂ Eq. (7.8 percent), respectively. Emissions from the Waste sector decreased by 27.9 MMT CO₂ Eq. (14.0 percent). Over the same period, estimates of net C sequestration for the Land Use, Land-Use Change, and Forestry sector (magnitude of emissions plus CO₂ removals from all LULUCF categories) increased by 24.5 MMT CO₂ Eq. (3.3 percent).

Figure 2-4: U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO₂ Eq.)

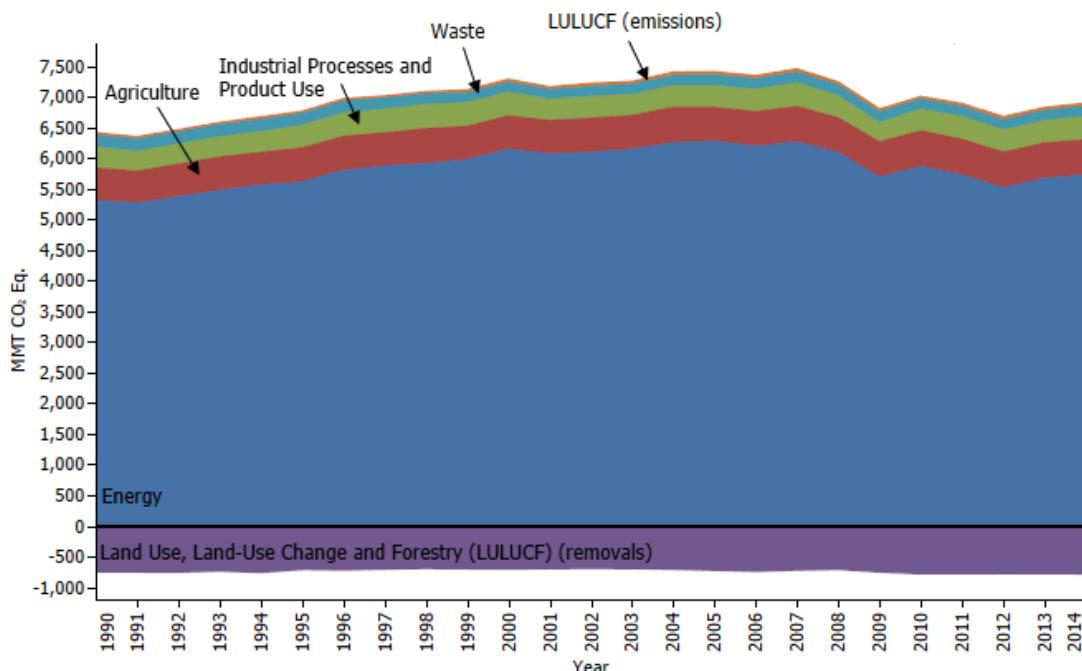


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (MMT CO₂ Eq.)

Chapter/IPCC Sector	1990	2005	2010	2011	2012	2013	2014
Energy	5,324.9	6,294.5	5,884.6	5,744.0	5,533.9	5,693.5	5,746.2
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
Natural Gas Systems	244.5	207.4	198.6	205.7	207.8	214.0	218.5
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Petroleum Systems	42.3	52.8	58.2	60.5	62.2	68.4	71.7
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Stationary Combustion	20.4	27.6	29.2	28.4	28.0	30.9	31.5
Mobile Combustion	46.9	37.1	25.9	24.7	22.2	20.3	18.4
Incineration of Waste	8.4	12.8	11.4	10.9	10.7	9.7	9.7
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3

Industrial Processes and Product Use	340.9	354.3	353.0	370.5	360.1	363.5	379.2
Substitution of Ozone Depleting Substances	0.3	99.7	141.2	145.3	150.2	154.6	161.2
Iron and Steel Production & Metallurgical Coke Production	99.7	66.6	55.7	59.9	54.2	52.2	55.4
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.8	27.5	27.3	26.4	26.5	26.5	26.6
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4
Aluminum Production	28.3	7.6	4.6	6.8	6.4	6.2	5.4
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0
Semiconductor Manufacture	3.6	4.7	4.0	5.1	4.5	4.2	4.7
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.7	1.5	1.2
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	532.0	552.2	582.3	583.1	583.3	575.3	573.6
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	51.1	72.9	78.1	78.9	81.2	78.9	78.7
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Waste	199.3	177.8	165.5	167.8	165.7	167.8	171.4
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Wastewater Treatment	19.0	20.2	19.9	19.9	19.8	19.6	19.5
Composting	0.7	3.5	3.5	3.5	3.7	3.9	3.9
Total Emissions^a	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5
Land Use, Land-Use Change, and Forestry	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)
Forest Land	(718.7)	(675.8)	(736.5)	(725.6)	(717.4)	(726.8)	(730.0)
Cropland	38.5	25.9	34.0	17.1	21.1	21.1	22.3
Grassland	26.2	39.8	32.0	43.0	43.9	44.1	44.2
Wetlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Settlements	(59.0)	(78.2)	(83.8)	(84.8)	(85.8)	(87.1)	(88.2)
Other	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
Net Emissions (Sources and Sinks)^b	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

^a Total emissions without LULUCF.

^b Net emissions with LULUCF.

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

Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO₂ emissions for the period of 1990 through 2014. In 2014, approximately 82 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 18 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy (see Figure 2-5 and Figure 2-6). A discussion of specific trends related to CO₂ as well as other greenhouse gas emissions from energy consumption is presented in the Energy chapter. Energy-related activities are also responsible for CH₄ and N₂O emissions (45 percent and 10 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: 2014 Energy Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)

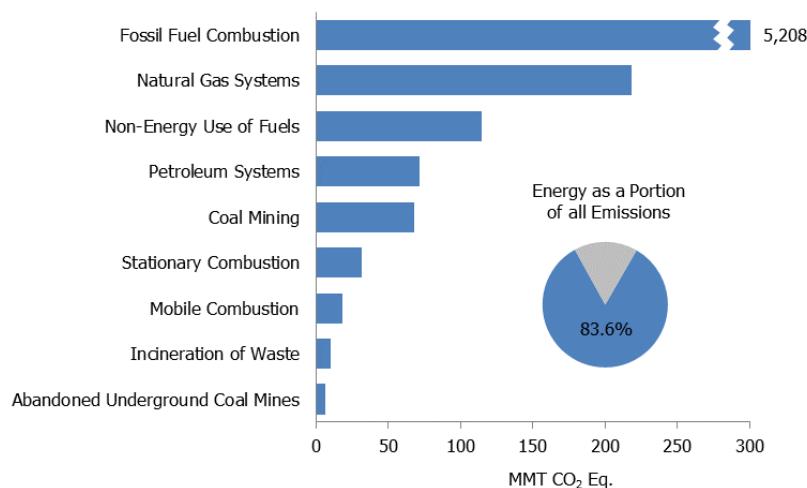


Figure 2-6: 2014 U.S. Fossil Carbon Flows (MMT CO₂ Eq.)

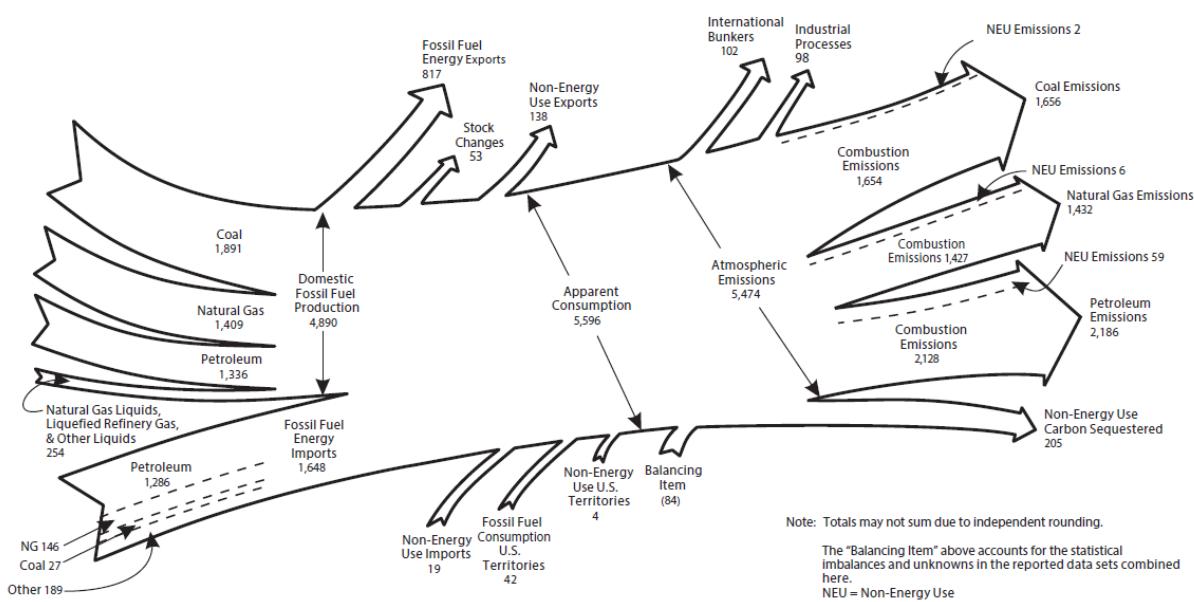


Table 2-4: Emissions from Energy (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	4,908.0	5,932.5	5,520.0	5,386.6	5,179.7	5,330.8	5,377.9
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
<i>Electricity Generation</i>	<i>1,820.8</i>	<i>2,400.9</i>	<i>2,258.4</i>	<i>2,157.7</i>	<i>2,022.2</i>	<i>2,038.1</i>	<i>2,039.3</i>
<i>Transportation</i>	<i>1,493.8</i>	<i>1,887.0</i>	<i>1,728.3</i>	<i>1,707.6</i>	<i>1,696.8</i>	<i>1,713.0</i>	<i>1,737.6</i>
<i>Industrial</i>	<i>842.5</i>	<i>828.0</i>	<i>775.5</i>	<i>773.3</i>	<i>782.9</i>	<i>812.2</i>	<i>813.3</i>
<i>Residential</i>	<i>338.3</i>	<i>357.8</i>	<i>334.6</i>	<i>326.8</i>	<i>282.5</i>	<i>329.7</i>	<i>345.1</i>
<i>Commercial</i>	<i>217.4</i>	<i>223.5</i>	<i>220.1</i>	<i>220.7</i>	<i>196.7</i>	<i>221.0</i>	<i>231.9</i>
<i>U.S. Territories</i>	<i>27.9</i>	<i>49.9</i>	<i>41.4</i>	<i>41.5</i>	<i>43.6</i>	<i>43.5</i>	<i>41.0</i>
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Natural Gas Systems	37.7	30.1	32.4	35.7	35.2	38.5	42.4
Incineration of Waste	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Petroleum Systems	3.6	3.9	4.2	4.2	3.9	3.7	3.6
<i>Biomass-Wood^a</i>	<i>215.2</i>	<i>206.9</i>	<i>192.5</i>	<i>195.2</i>	<i>194.9</i>	<i>211.6</i>	<i>217.7</i>
<i>International Bunker Fuels^b</i>	<i>103.5</i>	<i>113.1</i>	<i>117.0</i>	<i>111.7</i>	<i>105.8</i>	<i>99.8</i>	<i>103.2</i>
<i>Biomass-Ethanol^a</i>	<i>4.2</i>	<i>22.9</i>	<i>72.6</i>	<i>72.9</i>	<i>72.8</i>	<i>74.7</i>	<i>76.1</i>
CH₄	363.3	307.0	318.5	313.3	312.5	321.2	328.3
Natural Gas Systems	206.8	177.3	166.2	170.1	172.6	175.6	176.1
Petroleum Systems	38.7	48.8	54.1	56.3	58.4	64.7	68.1
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Stationary Combustion	8.5	7.4	7.1	7.1	6.6	8.0	8.1
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3
Mobile Combustion	5.6	2.7	2.3	2.2	2.2	2.1	2.0
Incineration of Waste	+	+	+	+	+	+	+
<i>International Bunker Fuels^b</i>	<i>0.2</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>
N₂O	53.6	55.0	46.1	44.0	41.7	41.4	40.0
Stationary Combustion	11.9	20.2	22.2	21.3	21.4	22.9	23.4
Mobile Combustion	41.2	34.4	23.6	22.4	20.0	18.2	16.3
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
<i>International Bunker Fuels^b</i>	<i>0.9</i>	<i>1.0</i>	<i>1.0</i>	<i>1.0</i>	<i>0.9</i>	<i>0.9</i>	<i>0.9</i>
Total	5,324.9	6,294.5	5,884.6	5,744.0	5,533.9	5,693.5	5,746.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^aEmissions from Wood Biomass and Ethanol 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.

^bEmissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

Carbon dioxide emissions from fossil fuel combustion are presented in Table 2-5 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Estimates of CO₂ emissions from fossil fuel combustion are calculated from these EIA “end-use sectors” based on total consumption and appropriate fuel properties (any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report). 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 (nonutility power producers can be included in this sector as long as they meet the electric power sector definition). 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 transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. EIA’s fuel consumption data for the industrial sector consists 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). EIA’s fuel consumption data for the residential sector consist of living quarters for private households. 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 and Figure 2-7 summarize CO₂ emissions from fossil fuel combustion by end-use sector. Figure 2-8 further describes the total emissions from fossil fuel combustion, separated by end-use sector, including CH₄ and N₂O in addition to CO₂.

Table 2-5: CO₂ Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation	1,496.8	1,891.8	1,732.7	1,711.9	1,700.6	1,717.0	1,741.7
Combustion	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6
Electricity	3.0	4.7	4.5	4.3	3.9	4.0	4.1
Industrial	1,529.2	1,564.6	1,416.5	1,398.0	1,375.7	1,407.0	1,406.8
Combustion	842.5	828.0	775.5	773.3	782.9	812.2	813.3
Electricity	686.7	736.6	641.0	624.7	592.8	594.7	593.6
Residential	931.4	1,214.1	1,174.6	1,117.5	1,007.8	1,064.6	1,080.3
Combustion	338.3	357.8	334.6	326.8	282.5	329.7	345.1
Electricity	593.0	856.3	840.0	790.7	725.3	734.9	735.2
Commercial	755.4	1,026.8	993.0	958.8	897.0	925.5	938.4
Combustion	217.4	223.5	220.1	220.7	196.7	221.0	231.9
Electricity	538.0	803.3	772.9	738.0	700.3	704.5	706.5
U.S. Territories^a	27.9	49.9	41.4	41.5	43.6	43.5	41.0
Total	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
Electricity Generation	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3

^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.

Notes: Combustion-related emissions from electricity generation are allocated based on aggregate national electricity consumption by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-7: 2014 CO₂ Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO₂ Eq.)

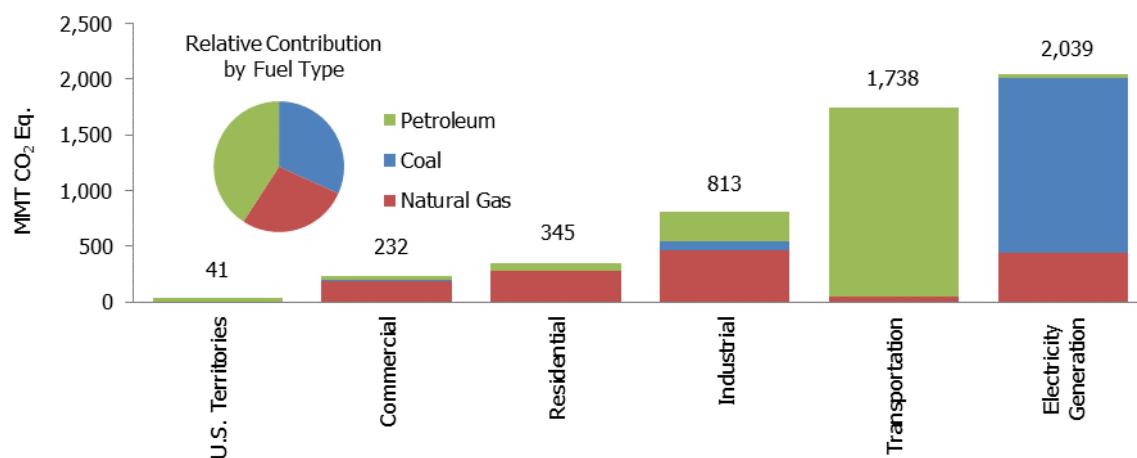
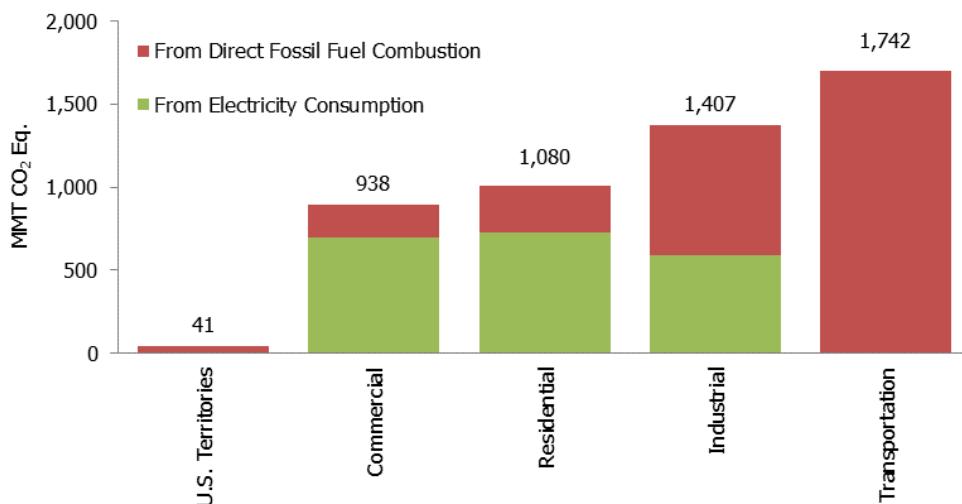


Figure 2-8: 2014 End-Use Sector Emissions of CO₂ from Fossil Fuel Combustion (MMT CO₂ Eq.)



The main driver of emissions in the Energy sector is CO₂ from fossil fuel combustion. Electricity generation is the largest emitter of CO₂, and electricity generators consumed 34 percent of U.S. energy from fossil fuels and emitted 39 percent of the CO₂ from fossil fuel combustion in 2014. Electricity generation emissions can also be allocated to the end-use sectors that are consuming that electricity, as presented in Table 2-5. The transportation end-use sector accounted for 1,741.7 MMT CO₂ Eq. in 2014 or approximately 33 percent of total CO₂ emissions from fossil fuel combustion. The industrial end-use sector accounted for 27 percent of CO₂ emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO₂ emissions from fossil fuel combustion. Both of these end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing 68 and 75 percent of emissions from the residential and commercial end-use sectors, respectively. Significant trends in emissions from energy source categories over the twenty five-year period from 1990 through 2014 included the following:

- Total CO₂ emissions from fossil fuel combustion increased from 4,740.7 MMT CO₂ Eq. in 1990 to 5,208.2 MMT CO₂ Eq. in 2014 – a 9.9 percent total increase over the twenty five-year period. From 2013 to 2014, these emissions increased by 50.6 MMT CO₂ Eq. (1.0 percent).
- Methane emissions from natural gas systems and petroleum systems (combined here) decreased very slightly from 245.5 MMT CO₂ Eq. in 1990 to 244.3 MMT CO₂ Eq. (1.2 MMT CO₂ Eq. or less than 1 percent) from 1990 to 2014. Natural gas systems CH₄ emissions decreased by 30.6 MMT CO₂ Eq. (14.8 percent) since 1990, largely due to a decrease in emissions from transmission, storage, and distribution. The decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and fugitives). The decrease in distribution emissions is largely attributed to increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating (M&R) stations. Petroleum systems CH₄ emissions increased by 29.4 MMT CO₂ Eq. (or 76 percent) since 1990. This increase is due primarily to increases in emissions from production equipment.
- Carbon dioxide emissions from non-energy uses of fossil fuels decreased by 3.8 MMT CO₂ Eq. (3.2 percent) from 1990 through 2014. Emissions from non-energy uses of fossil fuels were 114.3 MMT CO₂ Eq. in 2014, which constituted 2.1 percent of total national CO₂ emissions, approximately the same proportion as in 1990.
- Nitrous oxide emissions from stationary combustion increased by 11.5 MMT CO₂ Eq. (96.4 percent) from 1990 through 2014. Nitrous oxide emissions from this source increased primarily as a result of an increase in the number of coal fluidized bed boilers in the electric power sector.

- Nitrous oxide emissions from mobile combustion decreased by 24.9 MMT CO₂ Eq. (60.4 percent) from 1990 through 2014, primarily as a result of N₂O national emission control standards and emission control technologies for on-road vehicles.
- Carbon dioxide emissions from incineration of waste (9.4 MMT CO₂ Eq. in 2014) increased by 1.4 MMT CO₂ Eq. (18.2 percent) from 1990 through 2014, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.

The increase in CO₂ emissions from fossil fuel combustion in 2014 was a result of multiple factors, including: (1) colder winter conditions in the first quarter of 2014, which resulted in an increased demand for heating fuel in the residential and commercial sectors; (2) an increase in industrial production across multiple sectors, resulting in slight increases in industrial sector emissions;¹ and (3) an increase in transportation emissions resulting from an increase in VMT and fuel use across on-road transportation modes.

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.

Greenhouse gas emissions are produced as the by-products of many non-energy-related industrial activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO₂, CH₄, and N₂O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production, urea consumption, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and consumption, titanium dioxide production, phosphoric acid production, ferroalloy production, CO₂ consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, zinc production, and N₂O from product uses (see Figure 2-9). Industrial processes also release HFCs, PFCs, SF₆, and NF₃. In addition to their use as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF₆, NF₃, and others are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Table 2-6 presents greenhouse gas emissions from industrial processes by source category.

¹ Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See <<http://ghgdata.epa.gov/ghgp/main.do>>.

Figure 2-9: 2014 Industrial Processes and Product Use Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)

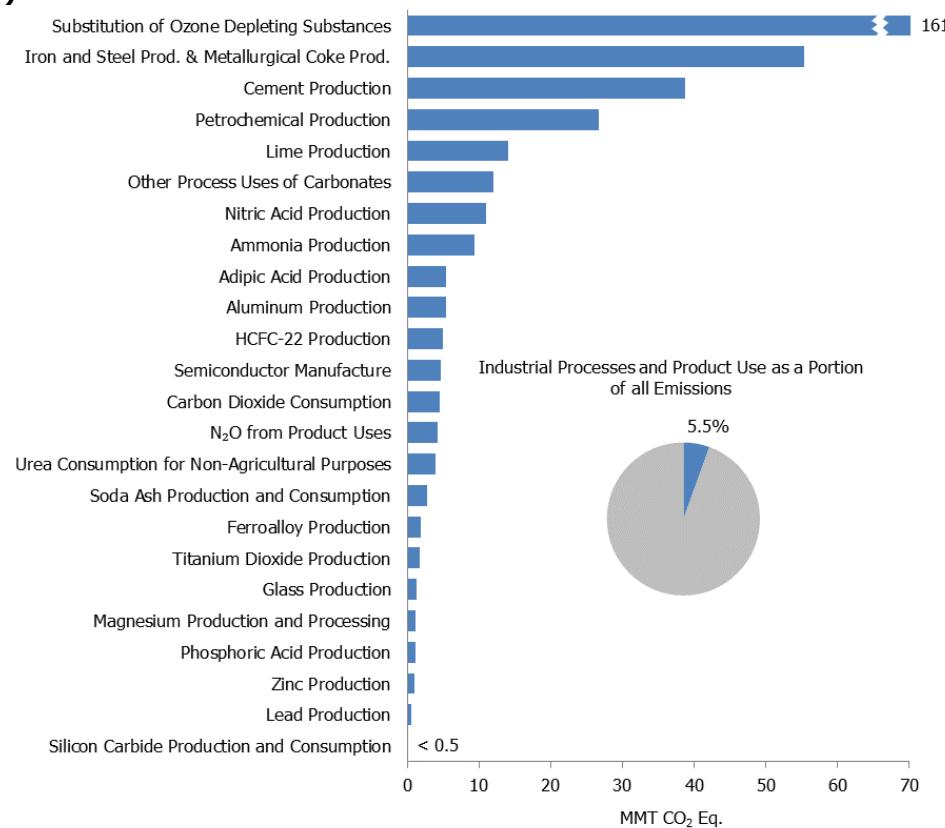


Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO ₂	207.1	190.3	168.8	172.9	169.5	171.7	178.1
Iron and Steel Production & Metallurgical Coke Production	99.7	66.5	55.7	59.9	54.2	52.2	55.4
<i>Iron and Steel Production</i>	97.2	64.5	53.6	58.5	53.7	50.4	53.4
<i>Metallurgical Coke Production</i>	2.5	2.0	2.1	1.4	0.5	1.8	1.9
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.6	27.4	27.2	26.3	26.5	26.4	26.5
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Aluminum Production	6.8	4.1	2.7	3.3	3.4	3.3	2.8
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon 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	0.1	0.1	0.1	0.1	0.2
Petrochemical Production	0.2	0.1	+	+	0.1	0.1	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production								
<i>Iron and Steel Production</i>	+	+	+	+	+	+	+	+
<i>Metallurgical Coke Production</i>	+	+	+	+	+	+	+	+
<i>Metallurgical Coke Production</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N₂O	31.6	22.8	20.1	25.5	20.4	19.1	20.8	
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9	
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4	
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	
Semiconductor Manufacturing	+	0.1	0.1	0.2	0.2	0.2	0.2	
HFCs	46.6	119.9	149.4	154.3	155.9	158.9	166.7	
Substitution of Ozone Depleting Substances ^a	0.3	99.7	141.2	145.3	150.2	154.6	161.2	
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0	
Semiconductor Manufacturing	0.2	0.2	0.2	0.2	0.2	0.2	0.3	
Magnesium Production and Processing	0.0	0.0	+	+	+	0.1	0.1	
PFCs	24.3	6.7	4.5	7.0	6.0	5.8	5.6	
Semiconductor Manufacturing	2.8	3.2	2.7	3.5	3.1	2.9	3.0	
Aluminum Production	21.5	3.4	1.9	3.5	2.9	3.0	2.5	
SF₆	31.1	14.0	9.5	10.0	7.6	7.2	7.3	
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6	
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.6	1.5	1.0	
Semiconductor Manufacturing	0.5	0.7	0.4	0.4	0.4	0.4	0.7	
NF₃	+	0.5	0.6	0.7	0.6	0.6	0.5	
Semiconductor Manufacturing	+	0.5	0.6	0.7	0.6	0.6	0.5	
Total	340.9	354.3	353.0	370.5	360.1	363.5	379.2	

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Overall, emissions from the IPPU sector increased by 11.2 percent from 1990 to 2014. Significant trends in emissions from IPPU source categories over the twenty five-year period from 1990 through 2014 included the following:

- Hydrofluorocarbon emissions from ODS substitutes have been increasing from small amounts in 1990 to 161.2 MMT CO₂ Eq. in 2014. This increase was in large part the result of efforts to phase out chlorofluorocarbons (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 hydrochlorofluorocarbons (HCFCs), which are interim substitutes in many applications, are themselves phased-out under the provisions of the *Copenhagen Amendments to the Montreal Protocol*.
- Combined CO₂ and CH₄ emissions from iron and steel production and metallurgical coke production increased by 6.0 percent to 55.4 MMT CO₂ Eq. from 2013 to 2014, and have declined overall by 44.3 MMT CO₂ Eq. (44.5 percent) from 1990 through 2014, due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Carbon dioxide emissions from ammonia production (9.4 MMT CO₂ Eq. in 2014) decreased by 3.6 MMT CO₂ Eq. (27.7 percent) 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.
- Urea consumption for non-agricultural purposes (4.0 MMT CO₂ Eq. in 2014) increased by 0.2 MMT CO₂ Eq. (5.9 percent) since 1990. From 1990 to 2007, emissions increased by 31 percent to a peak of 4.9 MMT CO₂ Eq., before decreasing by 19 percent to 2014 levels.

- In 2014, N₂O emissions from product uses constituted 1.0 percent of U.S. N₂O emissions. From 1990 to 2014, emissions from this source category decreased by 0.4 percent, though slight increases occurred in intermediate years.
- Nitrous oxide emissions from adipic acid production were 5.4 MMT CO₂ Eq. in 2014, and have decreased significantly since 1990 due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. Emissions from adipic acid production have decreased by 64.2 percent since 1990 and by 67.8 percent since a peak in 1995.
- PFC emissions from aluminum production decreased by 88.2 percent (18.9 MMT CO₂ Eq.) from 1990 to 2014, 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, and field burning of agricultural residues.

In 2014, agricultural activities were responsible for emissions of 573.6 MMT CO₂ Eq., or 8.3 percent of total U.S. greenhouse gas emissions. Methane and nitrous oxide were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented about 22.5 percent and 8.4 percent of total CH₄ emissions from anthropogenic activities, respectively, in 2014. Agricultural soil management activities, such as fertilizer use and other cropping practices, were the largest source of U.S. N₂O emissions in 2014, accounting for 78.9 percent. Figure 2-10 and Table 2-7 illustrate agricultural greenhouse gas emissions by source.

Figure 2-10: 2014 Agriculture Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)

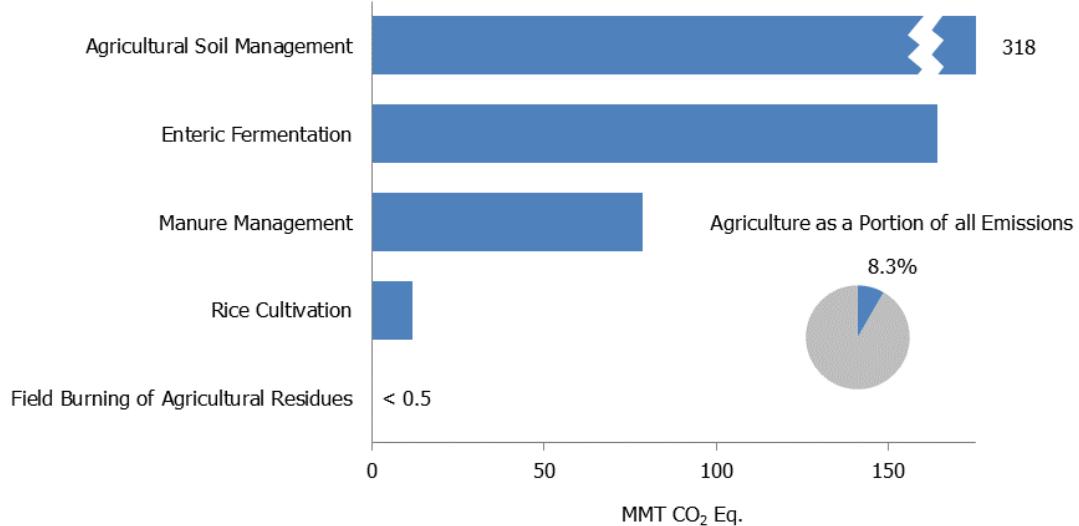


Table 2-7: Emissions from Agriculture (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	214.7	238.4	244.4	242.5	242.6	239.0	237.7
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N₂O	317.4	313.8	338.0	340.6	340.7	336.2	336.0
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	532.0	552.2	582.3	583.1	583.3	575.3	573.6

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Agriculture source categories include the following:

- Agricultural soils produced approximately 78.9 percent of N₂O emissions in the United States in 2014. Estimated emissions from this source in 2014 were 318.4 MMT CO₂ Eq. Annual N₂O emissions from agricultural soils fluctuated between 1990 and 2014, although overall emissions were 5.0 percent higher in 2014 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 second largest anthropogenic source of CH₄ emissions in the United States. In 2014, enteric fermentation CH₄ emissions were 164.3 MMT CO₂ Eq. (22.5 percent of total CH₄ emissions), which represents an increase of 0.1 MMT CO₂ Eq. (0.1 percent) since 1990. This increase in emissions from 1990 to 2014 in enteric fermentation generally follows the increasing trends in cattle populations. 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 underwent increases and the literature for dairy cow diets indicated a trend toward a decrease in feed digestibility for those years. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased.
- Overall, emissions from manure management increased 53.8 percent between 1990 and 2014. This encompassed an increase of 64.7 percent for CH₄, from 37.2 MMT CO₂ Eq. in 1990 to 61.2 MMT CO₂ Eq. in 2014; and an increase of 24.9 percent for N₂O, from 14.0 MMT CO₂ Eq. in 1990 to 17.5 MMT CO₂ Eq. in 2014. The majority of the increase observed in CH₄ resulted from swine and dairy cow manure, where emissions increased 44 and 118 percent, respectively, from 1990 to 2014. From 2013 to 2014, there was a 0.3 percent decrease in total CH₄ emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

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 alter the background C fluxes between biomass, soils, and the atmosphere. Forest management practices, tree planting in urban areas, the management of agricultural soils, and the landfilling of yard trimmings and food scraps have resulted in a net removal of CO₂ (sequestration of C) in the United States. Forests (including vegetation, soils, and harvested wood) accounted for 87 percent of total 2014 CO₂ removals, urban trees accounted for 11 percent, landfilled yard trimmings and food scraps accounted for 1.4 percent, and mineral and organic soil carbon stock changes from *Cropland Remaining Cropland* accounted for 1.0 percent of the total CO₂ removals in 2014. The net forest sequestration is a result of net forest growth, increasing forest area, and a net accumulation of carbon stocks in harvested wood pools. The net sequestration in urban forests is a result of net tree growth and increased urban forest size. In agricultural soils, mineral and organic soils sequester approximately as much C as is emitted

from these soils through liming and urea fertilization. The landfilled yard trimmings and food scraps net sequestration is due to the long-term accumulation of yard trimming and food scraps carbon in landfills.

LULUCF activities in 2014 resulted in a net increase in C stocks (i.e., net CO₂ removals) of 787.0 MMT CO₂ Eq. (Table 2-3).² This represents an offset of approximately 11.5 percent of total (i.e., gross) greenhouse gas emissions in 2014. Emissions from LULUCF activities in 2014 are 24.6 MMT CO₂ Eq. and represent 0.4 percent of total greenhouse gas emissions.³ Between 1990 and 2014, total C sequestration in the LULUCF sector increased by 4.5 percent, primarily due to an increase in the rate of net C accumulation in forest and urban tree C stocks.

Carbon dioxide removals are presented in Table 2-8 along with CO₂, CH₄, and N₂O emissions for LULUCF source categories. Liming and urea fertilization resulted in CO₂ emissions of 8.7 MMT CO₂ Eq. in 2014, an increase of about 22.2 percent relative to 1990. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO₂ emissions of 0.8 MMT CO₂ Eq. and CH₄ and N₂O emissions of less than 0.05 MMT CO₂ Eq. each. Nitrous oxide emissions from the application of synthetic fertilizers to forest soils have increased from 0.1 MMT CO₂ Eq. in 1990 to 0.5 MMT CO₂ Eq. in 2014. Settlement soils in 2014 resulted in N₂O emissions of 2.4 MMT CO₂ Eq., a 78.4 percent increase relative to 1990. Emissions from forest fires in 2014 resulted in CH₄ emissions of 7.3 MMT CO₂ and in N₂O emissions of 4.8 MMT CO₂ (see Table 2-8).

Table 2-8: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO₂ Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO₂ Flux^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
Forest Land Remaining Forest Land ^b	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Land Converted to Forest Land	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Cropland Remaining Cropland	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
Land Converted to Cropland	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Grassland Remaining Grassland	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Land Converted to Grassland	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Settlements Remaining Settlements	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
CO₂	8.1	9.0	9.6	8.9	11.0	9.0	9.5
Cropland Remaining Cropland: CO ₂ Emissions from Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Cropland Remaining Cropland: CO ₂ Emissions from Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
CH₄	3.3	9.9	3.3	6.6	11.1	7.3	7.4
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	3.3	9.9	3.3	6.6	11.1	7.3	7.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	3.6	9.3	5.0	7.3	10.3	7.7	7.7
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	2.2	6.5	2.2	4.4	7.3	4.8	4.8
Settlements Remaining Settlements: N ₂ O Fluxes from Settlement Soils ^c	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Forest Land Remaining Forest Land: N ₂ O Fluxes from Forest Soils ^d	0.1	0.5	0.5	0.5	0.5	0.5	0.5

² Net CO₂ flux 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*, *Settlements Remaining Settlements*, and *Other*.

³ LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions^e	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^f	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Net CO₂ flux 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, Settlements Remaining Settlements, and Other.*

^b Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^c Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^d Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^e LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^f The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Other significant trends from 1990 to 2014 in emissions from LULUCF categories include:

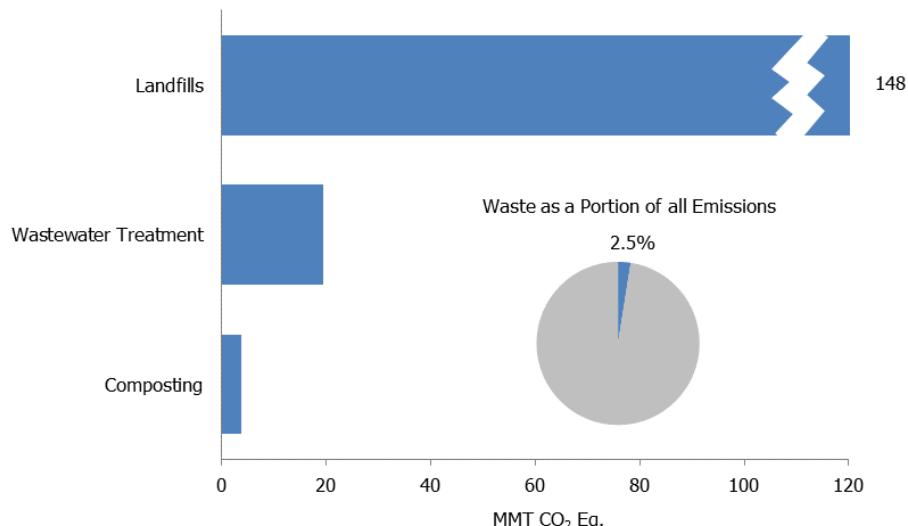
- Annual C sequestration by forest land (i.e., annual C stock accumulation in the five C pools for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) has increased by approximately 3 percent. This is primarily due to increased forest management and the effects of previous reforestation. The increase in intensive forest management resulted in higher growth rates and higher biomass density. The tree planting and conservation efforts of the 1970s and 1980s continue to have a significant impact on sequestration rates. Finally, the forested area in the United States increased over the past twenty five years, although only at an average rate of 0.1 percent per year.
- Annual C sequestration by urban trees has increased by 50.0 percent over the period from 1990 to 2014. This is primarily due to an increase in urbanized land area in the United States.
- Annual C sequestration in landfilled yard trimmings and food scraps has decreased by 55.4 percent since 1990. Food scrap generation has grown by 55 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 76 percent in 2014, the tonnage disposed in landfills has increased considerably (by 45 percent). Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11). In 2014, landfills were the third-largest source of U.S. anthropogenic CH₄ emissions, accounting for 20.2 percent of total U.S. CH₄ emissions.⁴ Additionally, wastewater treatment accounts for 11.4 percent of Waste emissions, 2.0 percent of U.S. CH₄ emissions, and 1.2 percent of N₂O emissions. Emissions of CH₄ and N₂O from composting grew from 1990 to 2014, and resulted in emissions of 3.9 MMT CO₂ Eq. in 2014. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-9.

⁴ 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 2-11: 2014 Waste Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)



Overall, in 2014, waste activities generated emissions of 171.4 MMT CO₂ Eq., or 2.5 percent of total U.S. greenhouse gas emissions.

Table 2-9: Emissions from Waste (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	195.6	171.8	159.4	161.5	159.2	161.1	164.7
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Wastewater Treatment	15.7	15.9	15.5	15.3	15.0	14.8	14.7
Composting	0.4	1.9	1.8	1.9	1.9	2.0	2.1
N₂O	3.7	6.0	6.1	6.4	6.5	6.6	6.7
Wastewater Treatment	3.4	4.3	4.5	4.7	4.8	4.8	4.8
Composting	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Total	199.3	177.8	165.5	167.8	165.7	167.8	171.4

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from waste source categories include the following:

- From 1990 to 2014, net CH₄ emissions from landfills decreased by 31.6 MMT CO₂ Eq. (17.6 percent), with small increases occurring in interim years. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted as well as reductions in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series,⁵ which has more than offset the additional CH₄ emissions resulting from an increase in the amount of municipal solid waste landfilled.
- Combined CH₄ and N₂O emissions from composting have generally increased since 1990, from 0.7 MMT CO₂ Eq. to 3.9 MMT CO₂ Eq. in 2014, which represents slightly more than a five-fold increase over the time series. The growth in composting since the 1990s is attributable to primarily two factors: (1) steady growth in population and residential housing, and (2) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills.
- From 1990 to 2014, CH₄ and N₂O emissions from wastewater treatment decreased by 1.0 MMT CO₂ Eq. (6.1 percent) and increased by 1.5 MMT CO₂ Eq. (44.1 percent), respectively. Methane emissions from

⁵ The CO₂ produced from combusted landfill CH₄ at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

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.

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; Industrial Processes and Product Use; Agriculture; LULUCF; and Waste. While it is important to use this characterization for consistency with UNFCCC reporting guidelines, it is also useful to allocate emissions into more commonly used sectoral categories. This section reports emissions by the following U.S. economic sectors: residential, commercial, industry, transportation, electricity generation, and agriculture, as well as U.S. Territories.

Using this categorization, emissions from electricity generation accounted for the largest portion (30 percent) of U.S. greenhouse gas emissions in 2014. Transportation activities, in aggregate, accounted for the second largest portion (26 percent). Emissions from industry accounted for about 21 percent of U.S. greenhouse gas emissions in 2014. In contrast to electricity generation and transportation, emissions from industry have in general declined over the past decade. The long-term decline in these emissions has been 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. The remaining 22 percent of U.S. greenhouse gas emissions were contributed by the residential, agriculture, and commercial sectors, plus emissions from U.S. Territories. The residential sector accounted for 6 percent, and primarily consisted of CO₂ emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 9 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N₂O emissions from agricultural soil management and CH₄ emissions from enteric fermentation, rather than CO₂ from fossil fuel combustion. The commercial sector accounted for roughly 7 percent of emissions, while U.S. Territories accounted for less than 1 percent. 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, and landfilling of yard trimmings.

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 2-12 shows the trend in emissions by sector from 1990 to 2014.

Figure 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq.)

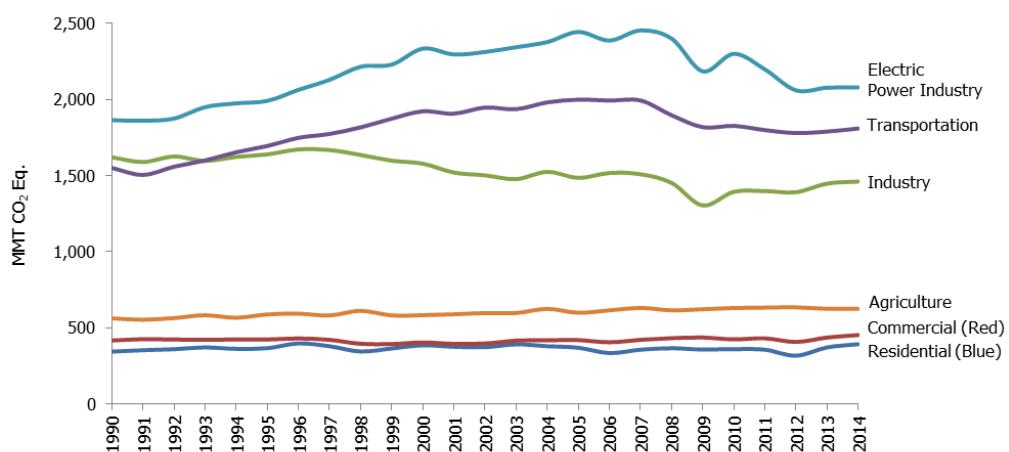


Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO₂ Eq. and Percent of Total in 2014)

Sector/Source	1990	2005	2010	2011	2012	2013	2014	Percent ^a
Electric Power Industry	1,864.8	2,443.9	2,300.5	2,198.1	2,060.7	2,078.0	2,080.7	30.3%
CO ₂ from Fossil Fuel Combustion	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3	29.7%
Stationary Combustion	7.7	16.5	18.9	18.0	18.2	19.5	20.0	0.3%
Incineration of Waste	8.4	12.8	11.4	10.9	10.7	9.7	9.7	0.1%
Other Process Uses of Carbonates	2.5	3.2	4.8	4.7	4.0	5.2	6.0	0.1%
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6	0.1%
Transportation	1,551.3	1,999.6	1,827.4	1,799.6	1,780.4	1,789.9	1,810.3	26.3%
CO ₂ from Fossil Fuel Combustion	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6	25.3%
Substitution of Ozone Depleting Substances	+ 67.1	65.6	60.2	55.1	49.8	47.2	47.2	0.7%
Mobile Combustion	45.7	35.3	24.0	22.7	20.2	18.3	16.3	0.2%
Non-Energy Use of Fuels	11.8	10.2	9.5	9.0	8.3	8.8	9.1	0.1%
Industry	1,620.9	1,486.2	1,394.5	1,399.0	1,392.1	1,448.2	1,461.7	21.3%
CO ₂ from Fossil Fuel Combustion	811.4	780.6	727.4	723.4	731.5	761.8	762.1	11.1%
Natural Gas Systems	244.5	207.4	198.6	205.7	207.8	214.0	218.5	3.2%
Non-Energy Use of Fuels	100.6	120.6	100.8	95.8	93.5	109.1	101.6	1.5%
Petroleum Systems	42.3	52.8	58.2	60.5	62.2	68.4	71.7	1.0%
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6	1.0%
Iron and Steel Production	99.7	66.6	55.7	59.9	54.2	52.2	55.4	0.8%
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8	0.6%
Petrochemical Production	21.8	27.5	27.3	26.4	26.5	26.5	26.6	0.4%
Substitution of Ozone Depleting Substances	+ 7.3	15.3	17.0	18.7	20.4	22.2	22.2	0.3%
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1	0.2%
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9	0.2%
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4	0.1%
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3	0.1%
Other Process Uses of Carbonates	2.5	3.2	4.8	4.7	4.0	5.2	6.0	0.1%
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4	0.1%
Aluminum Production	28.3	7.6	4.6	6.8	6.4	6.2	5.4	0.1%
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0	0.1%
Semiconductor Manufacture	3.6	4.7	4.0	5.1	4.5	4.2	4.7	0.1%
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5	0.1%
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	0.1%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0	0.1%
Stationary Combustion	4.9	4.6	3.9	3.9	3.9	3.9	3.9	0.1%
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8	+
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9	+
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8	+
Mobile Combustion	0.9	1.3	1.4	1.4	1.4	1.5	1.5	+
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3	+
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.7	1.5	1.2	+
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1	+
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0	+
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5	+
Silicon Carbide Production and Consumption	0.4	0.2	0.2	0.2	0.2	0.2	0.2	+
Agriculture	563.4	600.2	631.1	633.7	635.4	626.3	625.4	9.1%
N ₂ O from Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4	4.6%
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3	2.4%
Manure Management	51.1	72.9	78.1	78.9	81.2	78.9	78.7	1.1%
CO ₂ from Fossil Fuel Combustion	31.0	47.4	48.2	49.9	51.4	50.4	51.2	0.7%
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9	0.2%

Mobile Combustion	0.3	0.5	0.5	0.5	0.6	0.6	0.6	+
Field Burning of Agricultural Residues	0.3	0.3	0.4	0.4	0.4	0.4	0.4	+
Stationary Combustion	+	+	+	+	+	+	+	+
Commercial	418.1	420.3	425.5	432.1	408.5	437.5	453.9	6.6%
CO ₂ from Fossil Fuel Combustion	217.4	223.5	220.1	220.7	196.7	221.0	231.9	3.4%
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0	2.2%
Substitution of Ozone Depleting Substances	+	17.6	38.5	42.1	44.9	47.4	49.2	0.7%
Wastewater Treatment	15.7	15.9	15.5	15.3	15.0	14.8	14.7	0.2%
Human Sewage	3.4	4.3	4.5	4.7	4.8	4.8	4.8	0.1%
Composting	0.7	3.5	3.5	3.5	3.7	3.9	3.9	0.1%
Stationary Combustion	1.4	1.4	1.4	1.4	1.2	1.3	1.4	+
Residential	344.9	370.4	361.2	357.6	318.4	372.6	393.7	5.7%
CO ₂ from Fossil Fuel Combustion	338.3	357.8	334.6	326.8	282.5	329.7	345.1	5.0%
Substitution of Ozone Depleting Substances	0.3	7.7	21.8	25.9	31.4	37.0	42.6	0.6%
Stationary Combustion	6.3	4.9	4.8	4.9	4.5	5.9	6.0	0.1%
U.S. Territories	33.7	58.2	45.3	45.4	47.6	47.5	44.7	0.7%
CO ₂ from Fossil Fuel Combustion	27.9	49.9	41.4	41.5	43.6	43.5	41.0	0.6%
Non-Energy Use of Fuels	5.7	8.1	3.7	3.7	3.8	3.8	3.5	0.1%
Stationary Combustion	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5	100.0%
LULUCF Sector Total^b	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)	(11.1%)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0	88.9%

Note: Total emissions presented without LULUCF. Total net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO₂ Eq. or 0.05 percent.

^a Percent of total (gross) emissions excluding emissions from LULUCF for 2014.

^b The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Emissions with Electricity Distributed to Economic Sectors

It can also be useful to view greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). The generation, transmission, and distribution of electricity, which is the largest economic sector in the United States, accounted for 30 percent of total U.S. greenhouse gas emissions in 2014. Emissions increased by 12 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. Electricity generation-related emissions increased from 2013 to 2014 by 0.1 percent, primarily due to increased CO₂ emissions from fossil fuel combustion. Electricity sales to the residential and commercial end-use sectors in 2014 increased approximately 0.9 percent and 1.1 percent, respectively. The trend in the residential and commercial sectors can largely be attributed to colder more energy-intensive winter conditions compared to 2013. Electricity sales to the industrial sector in 2014 increased by approximately 1.2 percent. Overall, in 2014, the amount of electricity generated (in kWh) increased by 1.1 percent from the previous year. Despite this increase in generation, CO₂ emissions from the electric power sector increased by 0.1 percent as the consumption of petroleum for electricity generation increased by 15.8 percent in 2014 and the consumption of CO₂-intensive coal and natural gas for electricity generation decreased by 0.1 and 0.2 percent, respectively. Table 2-11 provides a detailed summary of emissions from electricity generation-related activities.

Table 2-11: Electricity Generation-Related Greenhouse Gas Emissions (MMT CO₂ Eq.)

Gas/Fuel Type or Source	1990	2005	2010	2011	2012	2013	2014
CO ₂	1,831.2	2,416.5	2,274.2	2,172.9	2,036.6	2,052.8	2,054.8
Fossil Fuel Combustion	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3
Coal	1,547.6	1,983.8	1,827.6	1,722.7	1,511.2	1,571.3	1,570.4
Natural Gas	175.3	318.8	399.0	408.8	492.2	444.0	443.2

Petroleum	97.5	97.9	31.4	25.8	18.3	22.4	25.3
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Incineration of Waste	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Other Process Uses of Carbonates	2.5	3.2	4.8	4.7	4.0	5.2	6.0
CH₄	0.3	0.5	0.5	0.4	0.4	0.4	0.4
Stationary Sources (Elec Gen)	0.3	0.5	0.5	0.4	0.4	0.4	0.4
Incineration of Waste	+	+	+	+	+	+	+
N₂O	7.8	16.4	18.8	17.9	18.1	19.4	19.9
Stationary Sources (Elec Gen)	7.4	16.0	18.5	17.6	17.8	19.1	19.6
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
SF₆	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Total	1,864.8	2,443.9	2,300.5	2,198.1	2,060.7	2,078.0	2,080.7

+ Does not exceed 0.05 MMT CO₂ Eq.

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

Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electricity generation 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 consumption (EIA 2016 and Duffield 2006). These source categories include CO₂ from Fossil Fuel Combustion, CH₄ and N₂O from Stationary Combustion, Incineration of Waste, Other Process Uses of Carbonates, and SF₆ from Electrical Transmission and Distribution Systems. Note that only 50 percent of the Other Process Uses of Carbonates emissions were associated with electricity generation 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 are distributed among these sectors, industrial activities account for the largest share of total U.S. greenhouse gas emissions (29.2 percent), followed closely by emissions from transportation (26.4 percent). Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included. In all sectors except agriculture, CO₂ accounts for more than 80 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 electricity generation distributed to them. Figure 2-13 shows the trend in these emissions by sector from 1990 to 2014.

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

Figure 2-13: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors (MMT CO₂ Eq.)

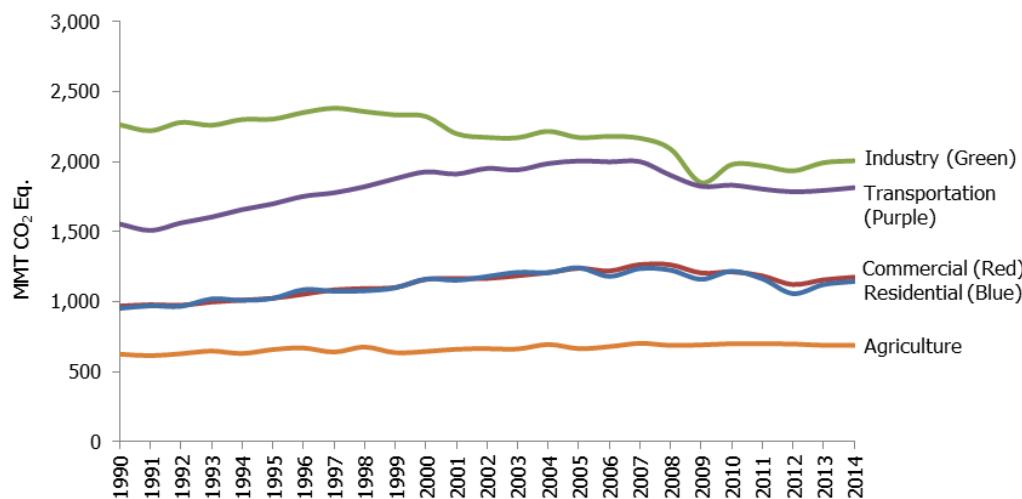


Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO₂ Eq.) and Percent of Total in 2014

Sector/Gas	1990	2005	2010	2011	2012	2013	2014	Percent ^a
Industry	2,262.9	2,171.9	1,979.1	1,970.0	1,934.0	1,992.5	2,005.7	29.2%
Direct Emissions	1,620.9	1,486.2	1,394.5	1,399.0	1,392.1	1,448.2	1,461.7	21.3%
CO ₂	1,157.9	1,122.3	1,028.8	1,027.2	1,029.5	1,079.6	1,081.7	15.7%
CH ₄	351.4	298.9	310.9	305.8	305.5	312.9	320.0	4.7%
N ₂ O	35.4	26.7	23.7	29.1	24.0	22.7	24.5	0.4%
HFCs, PFCs, SF ₆ , and NF ₃	76.3	38.2	31.1	36.9	33.1	33.0	35.5	0.5%
Electricity-Related	642.0	685.7	584.5	571.0	541.9	544.3	544.0	7.9%
CO ₂	630.4	678.0	577.9	564.4	535.6	537.7	537.2	7.8%
CH ₄	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+
N ₂ O	2.7	4.6	4.8	4.7	4.8	5.1	5.2	0.1%
SF ₆	8.7	3.0	1.8	1.8	1.5	1.4	1.5	+
Transportation	1,554.4	2,004.4	1,832.0	1,803.9	1,784.3	1,794.0	1,814.5	26.4%
Direct Emissions	1,551.3	1,999.6	1,827.4	1,799.6	1,780.4	1,789.9	1,810.3	26.3%
CO ₂	1,505.6	1,897.2	1,737.8	1,716.6	1,705.0	1,721.8	1,746.7	25.4%
CH ₄	5.4	2.4	1.9	1.8	1.8	1.7	1.6	+
N ₂ O	40.3	32.9	22.1	20.9	18.5	16.6	14.7	0.2%
HFCs ^b	+	67.1	65.6	60.2	55.1	49.8	47.2	0.7%
Electricity-Related	3.1	4.8	4.6	4.3	3.9	4.1	4.1	0.1%
CO ₂	3.1	4.8	4.5	4.3	3.9	4.0	4.1	0.1%
CH ₄	+	+	+	+	+	+	+	+
N ₂ O	+	+	+	+	+	+	+	+
SF ₆	+	+	+	+	+	+	+	+
Commercial	969.1	1,238.0	1,212.8	1,183.9	1,122.1	1,155.8	1,174.7	17.1%
Direct Emissions	418.1	420.3	425.5	432.1	408.5	437.5	453.9	6.6%
CO ₂	217.4	223.5	220.1	220.7	196.7	221.0	231.9	3.4%
CH ₄	196.6	172.8	160.5	162.5	160.1	162.2	165.8	2.4%
N ₂ O	4.1	6.4	6.4	6.7	6.7	6.9	7.0	0.1%
HFCs	+	17.6	38.5	42.1	44.9	47.4	49.2	0.7%
Electricity-Related	551.0	817.7	787.3	751.9	713.6	718.3	720.8	10.5%
CO ₂	541.1	808.5	778.3	743.3	705.2	709.5	711.8	10.4%
CH ₄	0.1	0.2	0.2	0.2	0.1	0.2	0.2	+
N ₂ O	2.3	5.5	6.4	6.1	6.3	6.7	6.9	0.1%

SF ₆	7.5	3.5	2.4	2.3	1.9	1.9	1.9	+
Residential	952.2	1,242.1	1,216.9	1,163.1	1,057.5	1,121.9	1,143.8	16.6%
Direct Emissions	344.9	370.4	361.2	357.6	318.4	372.6	393.7	5.7%
CO ₂	338.3	357.8	334.6	326.8	282.5	329.7	345.1	5.0%
CH ₄	5.2	4.1	4.0	4.0	3.7	5.0	5.0	0.1%
N ₂ O	1.0	0.9	0.8	0.8	0.7	1.0	1.0	+
HFCs	0.3	7.7	21.8	25.9	31.4	37.0	42.6	0.6%
Electricity-Related	607.3	871.7	855.7	805.5	739.1	749.3	750.2	10.9%
CO ₂	596.4	861.9	845.9	796.3	730.4	740.2	740.8	10.8%
CH ₄	0.1	0.2	0.2	0.2	0.2	0.2	0.2	+
N ₂ O	2.5	5.8	7.0	6.6	6.5	7.0	7.2	0.1%
SF ₆	8.3	3.8	2.6	2.5	2.0	1.9	2.0	+
Agriculture	624.8	664.2	699.5	699.1	697.5	688.3	687.0	10.0%
Direct Emissions	563.4	600.2	631.1	633.7	635.4	626.3	625.4	9.1%
CO ₂	31.0	47.4	48.2	49.9	51.4	50.4	51.2	0.7%
CH ₄	214.8	238.6	244.6	242.7	242.8	239.2	237.9	3.5%
N ₂ O	317.6	314.1	338.3	341.0	341.1	336.6	336.4	4.9%
Electricity-Related	61.3	64.1	68.4	65.4	62.1	62.1	61.6	0.9%
CO ₂	60.2	63.4	67.6	64.7	61.4	61.3	60.8	0.9%
CH ₄	+	+	+	+	+	+	+	+
N ₂ O	0.3	0.4	0.6	0.5	0.5	0.6	0.6	+
SF ₆	0.8	0.3	0.2	0.2	0.2	0.2	0.2	+
U.S. Territories	33.7	58.2	45.3	45.4	47.6	47.5	44.7	0.7%
Total Emissions	6,397.1	7,378.8	6,985.5	6,865.4	6,643.0	6,800.0	6,870.5	100.0%
LULUCF Sector Total^c	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)	(11.1%)
Net Emissions (Sources and Sinks)	5,659.2	6,680.3	6,219.0	6,103.4	5,893.3	6,040.4	6,108.0	88.9%

Note: Total emissions presented without LULUCF. Net emissions presented with LULUCF.

+ Does not exceed 0.05 MMT CO₂ Eq. or 0.05 percent.

^a Percent of total gross emissions excluding emissions from LULUCF for year 2014.

^b Includes primarily HFC-134a.

^c The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

Notes: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector. Totals may not sum due to independent rounding.

Industry

The industry end-use sector includes CO₂ emissions from fossil fuel combustion from all manufacturing facilities, in aggregate. 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 methane emissions from petroleum and natural gas systems, fugitive CH₄ emissions from coal mining, by-product CO₂ emissions from cement manufacture, and HFC, PFC, SF₆, and NF₃ byproduct emissions from semiconductor manufacture, to name a few. Since 1990, industrial sector emissions have declined. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. In theory, emissions from the industrial end-use sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions. In addition, 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) also have a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 26 percent of U.S. greenhouse gas emissions in 2014. The largest sources of transportation greenhouse gases in 2014 were passenger cars (42.0 percent), freight trucks (22.5 percent), light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (18.6 percent), commercial aircraft (6.4 percent), rail (2.6 percent), pipelines

(2.6 percent), and ships and boats (1.6 percent). These figures include direct CO₂, CH₄, and N₂O emissions from fossil fuel combustion used in transportation 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 2014, total transportation emissions rose by 17 percent 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 2014). The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 37 percent from 1990 to 2014, 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, the rate of VMT growth slowed while average new vehicle fuel economy began to increase. Average new vehicle fuel economy has improved almost every year since 2005, and the truck share has decreased to about 41 percent of new vehicles in Model Year (MY) 2014 (EPA 2015a). Between 2013 and 2014, VMT increased by only 1.3 percent. Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

From 2008 to 2009, CO₂ emissions from the transportation end-use sector declined 4.2 percent. The decrease in emissions could largely be attributed to decreased economic activity in 2009 and an associated decline in the demand for transportation. Modes such as medium- and heavy-duty trucks were significantly impacted by the decline in freight transport. After reaching a decadal low in 2012, CO₂ emissions from the transportation end-use sector stabilized and grew slowly in 2013 and 2014 as the economic recovery gained strength.

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 CO₂ from fossil fuel combustion, which increased by 16 percent from 1990 to 2014. This rise in CO₂ emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 47.2 MMT CO₂ Eq. in 2014, led to an increase in overall emissions from transportation activities of 17 percent.

Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO₂ Eq.)

Gas/Vehicle	1990	2005	2010	2011	2012	2013	2014
Passenger Cars	656.6	708.9	783.6	774.3	767.9	763.2	762.5
CO ₂	629.3	660.1	742.0	736.9	735.5	735.5	737.6
CH ₄	3.2	1.2	1.2	1.2	1.1	1.0	1.0
N ₂ O	24.1	15.9	12.9	12.3	10.7	9.4	8.0
HFCs	+	31.7	27.5	23.9	20.6	17.3	16.0
Light-Duty Trucks	335.6	551.5	348.9	332.0	326.0	323.4	338.1
CO ₂	321.1	504.3	308.8	294.8	291.9	292.5	309.2
CH ₄	1.7	0.8	0.4	0.4	0.3	0.3	0.3
N ₂ O	12.8	13.2	5.5	5.0	4.4	3.9	3.6
HFCs	+	33.3	34.2	31.7	29.3	26.7	25.0
Medium- and Heavy-Duty Trucks	231.1	398.2	389.7	388.4	388.7	395.7	407.4
CO ₂	230.1	395.4	385.6	383.9	383.7	390.3	402.0
CH ₄	0.3	0.1	0.1	0.1	0.1	0.1	0.1
N ₂ O	0.7	1.1	1.1	1.0	0.9	0.9	0.9
HFCs	+	1.5	2.9	3.4	3.9	4.4	4.4
Buses	8.4	12.1	15.8	16.8	17.8	18.0	19.1
CO ₂	8.4	11.8	15.3	16.2	17.3	17.5	18.6
CH ₄	+	+	+	+	+	+	+
N ₂ O	+	+	0.1	0.1	0.1	0.1	0.1
HFCs	+	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	1.8	1.7	3.7	3.6	4.2	4.0	3.9
CO ₂	1.7	1.6	3.6	3.6	4.1	3.9	3.8

CH ₄	+	+	+	+	+	+	+
N ₂ O	+	+	+	+	+	+	+
Commercial Aircraft^a	110.9	134.0	114.4	115.7	114.3	115.4	116.3
CO ₂	109.9	132.7	113.3	114.6	113.3	114.3	115.2
CH ₄	+	+	+	+	+	+	+
N ₂ O	1.0	1.2	1.0	1.1	1.0	1.1	1.1
Other Aircraft^b	78.3	59.7	40.4	34.2	32.1	34.7	35.2
CO ₂	77.5	59.1	40.1	33.9	31.8	34.4	34.9
CH ₄	0.1	0.1	+	+	+	+	+
N ₂ O	0.7	0.5	0.4	0.3	0.3	0.3	0.3
Ships and Boats^c	44.9	44.9	44.7	46.4	40.1	39.4	28.6
CO ₂	44.3	44.3	44.0	45.5	39.3	38.7	28.0
CH ₄	+	+	+	+	+	+	+
N ₂ O	0.6	0.6	0.8	0.8	0.7	0.7	0.5
HFCs	+	+	+	+	+	+	+
Rail	39.0	51.1	44.2	45.9	44.6	45.5	47.6
CO ₂	38.5	50.3	43.1	44.7	43.4	44.2	45.7
CH ₄	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N ₂ O	0.3	0.4	0.3	0.3	0.3	0.3	0.4
HFCs	+	0.3	0.6	0.7	0.8	0.9	1.4
Other Emissions from Electricity Generation ^d	0.1	0.1	+	+	+	+	+
Pipelines^e	36.0	32.2	37.1	37.8	40.3	45.9	46.5
CO ₂	36.0	32.2	37.1	37.8	40.3	45.9	46.5
Lubricants	11.8	10.2	9.5	9.0	8.3	8.8	9.1
CO ₂	11.8	10.2	9.5	9.0	8.3	8.8	9.1
Total Transportation	1,554.4	2,004.4	1,832.0	1,803.9	1,784.3	1,794.0	1,814.5
<i>International Bunker</i>	<i>104.5</i>	<i>114.2</i>	<i>118.1</i>	<i>112.8</i>	<i>106.8</i>	<i>100.7</i>	<i>104.2</i>

+ Does not exceed 0.05 MMT CO₂ 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 electricity generation are a result of waste incineration (as the majority of municipal solid waste is combusted in “trash-to-steam” electricity generation plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electricity generation plants).

^e CO₂ estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH₄ and N₂O, these emissions are not directly attributed to pipelines in the U.S. Inventory.

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

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.

Commercial

The commercial sector is heavily reliant on electricity for meeting energy needs, with electricity consumption 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 residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. Landfills and wastewater treatment are included in this sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions decreasing slightly.

Residential

The residential sector is heavily reliant on electricity for meeting energy needs, with electricity consumption 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 sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long-term, this sector is also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

Agriculture

The agriculture end-use sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2014, agricultural soil management was the largest source of N₂O emissions, and enteric fermentation was the second largest source of CH₄ emissions in the United States. This sector also includes small amounts of CO₂ emissions from fossil fuel combustion by motorized farm equipment like tractors. The agriculture sector is less reliant on electricity than the other sectors.

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 sectors improves communication of the report's findings.

In the Electricity Generation economic sector, CO₂ emissions from the combustion of fossil fuels included in the EIA electric utility fuel consuming sector are apportioned to this economic sector. Stationary combustion emissions of CH₄ and N₂O are also based on the EIA electric utility sector. Additional sources include CO₂, CH₄, and N₂O from waste incineration, as the majority of municipal solid waste is combusted in “trash-to-steam” electricity generation plants. The Electricity Generation economic sector also includes SF₆ from Electrical Transmission and Distribution, and a portion of CO₂ from Other Process Uses of Carbonates (from pollution control equipment installed in electricity generation plants).

In the Transportation economic sector, the CO₂ emissions from the combustion of fossil fuels included in the EIA transportation fuel consuming sector are apportioned to this economic sector (additional analyses and refinement of the EIA data is further explained in the Energy chapter of this report). Emissions of CH₄ and N₂O from Mobile Combustion are also apportioned to this economic sector based on the EIA transportation fuel consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned based on their specific end-uses within the source category, with emissions from transportation refrigeration/air-conditioning systems to this economic sector. Finally, CO₂ emissions from Non-Energy Uses of Fossil Fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

For the Industry economic sector, the CO₂ emissions from the combustion of fossil fuels included in the EIA industrial fuel consuming sector, minus the agricultural use of fuel explained below, are apportioned to this economic sector. The CH₄ and N₂O emissions from stationary and mobile combustion are also apportioned to this economic sector based on the EIA industrial fuel consuming sector, minus emissions apportioned to the Agriculture economic sector described below. Substitution of Ozone Depleting Substance emissions are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector. Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector have been apportioned to this 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 such activities 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 CO₂ from Other Process Uses of Carbonates (from pollution control equipment installed in large industrial facilities) are also included in the Industry economic sector. Finally,

all remaining CO₂ 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.

As agriculture equipment is included in EIA's industrial fuel consuming sector surveys, additional data is used to extract the fuel used by agricultural equipment, to allow for accurate reporting in the Agriculture economic sector from all sources of emissions, such as motorized farming equipment. Energy consumption estimates are obtained from Department of Agriculture survey data, in combination with separate EIA fuel sales reports. This supplementary data is used to apportion some of the CO₂ emissions from fossil fuel combustion, and CH₄ and N₂O emissions from stationary and mobile combustion, to the Agriculture economic sector. The other emission sources included in this economic sector are intuitive for the agriculture sectors, such as N₂O emissions from Agricultural Soils, CH₄ from Enteric Fermentation, CH₄ and N₂O from Manure Management, CH₄ from Rice Cultivation, CO₂ emissions from Liming and Urea Application, and CH₄ and N₂O from Forest Fires. N₂O emissions from the Application of Fertilizers to tree plantations (termed "forest land" by the IPCC) are also included in the Agriculture economic sector.

The Residential economic sector includes the CO₂ emissions from the combustion of fossil fuels reported for the EIA residential sector. Stationary combustion emissions of CH₄ and N₂O are also based on the EIA residential fuel consuming sector. Substitution of Ozone Depleting Substances are apportioned based on their specific end-uses within the source category, with emissions from residential air-conditioning systems to this economic sector. N₂O 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 the CO₂ emissions from the combustion of fossil fuels reported in the EIA commercial fuel consuming sector data. Emissions of CH₄ and N₂O from Mobile Combustion are also apportioned to this economic sector based on the EIA transportation fuel consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned based on their specific end-uses within the source category, with emissions from commercial refrigeration/air-conditioning systems apportioned to this economic sector. Public works sources including direct CH₄ from Landfills and CH₄ and N₂O from Wastewater Treatment and Composting are also included in this economic sector.

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

Total 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 consumption, 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 electricity consumption, because the electric power industry—utilities and non UTILITIES combined—was the largest source of U.S. greenhouse gas emissions in 2014; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) 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. Greenhouse gas emissions in the United States have grown at an average annual rate of 0.3 percent since 1990. Since 1990, this rate is slightly slower than that for total energy and for fossil fuel consumption, and much slower than that for electricity consumption, overall gross domestic product and national population (see Table 2-14 and Figure 2-14).

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

Chapter/IPCC Sector	1990	2005	2010	2011	2012	2013	2014	Growth ^a
Greenhouse Gas Emissions ^b	100	115	109	107	104	106	107	0.3%
Energy Consumption ^c	100	118	116	115	112	116	117	0.7%
Fossil Fuel Consumption ^c	100	119	112	110	107	110	111	0.5%
Electricity Consumption ^c	100	134	137	137	135	136	138	1.4%
GDP ^d	100	159	165	168	171	174	178	2.5%
Population ^e	100	118	124	125	126	126	127	1.0%

^a Average annual growth rate

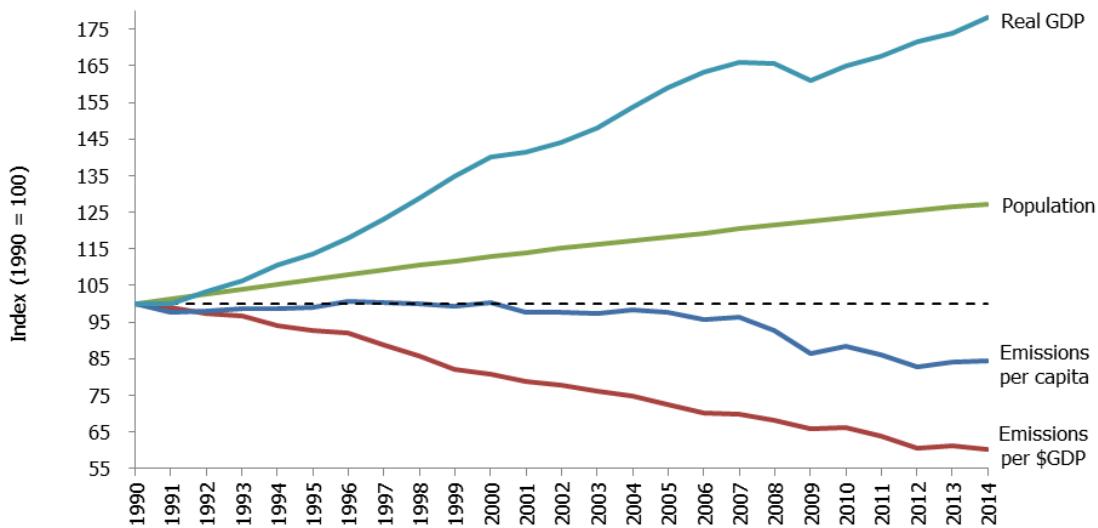
^b GWP-weighted values

^c Energy-content-weighted values (EIA 2016)

^d Gross Domestic Product in chained 2009 dollars (BEA 2016)

^e U.S. Census Bureau (2015)

Figure 2-14: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2016), U.S. Census Bureau (2015), and emission estimates in this report.

2.3 Indirect Greenhouse Gas Emissions (CO₂, NO_x, NMVOCs, and SO₂)

The reporting requirements of the UNFCCC⁷ request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO₂. These gases do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or, in the case of SO₂, 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 NO₂) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from N₂O. 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, SO₂ 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.

⁷ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>>.

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 CO's interaction with the hydroxyl radical—the major atmospheric sink for CH₄ emissions—to form CO₂. Therefore, increased atmospheric concentrations of CO limit the number of hydroxyl molecules (OH) available to destroy CH₄.

Since 1970, the United States has published estimates of emissions of CO, NO_x, NMVOCs, and SO₂ (EPA 2015),⁸ 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 SO₂ (kt)

Gas/Activity	1990	2005	2010	2011	2012	2013	2014
NO_x	21,783	17,421	12,565	12,416	11,778	11,195	10,633
Mobile Fossil Fuel Combustion	10,862	10,295	7,290	7,294	6,788	6,283	5,777
Stationary Fossil Fuel Combustion	10,023	5,858	4,092	3,807	3,567	3,579	3,522
Oil and Gas Activities	139	321	545	622	622	622	622
Industrial Processes and Product Use	592	572	472	452	452	452	452
Forest Fires	78	239	80	159	266	177	177
Waste Combustion	82	128	77	73	73	73	73
Agricultural Burning	6	6	7	8	8	8	8
Waste	+	2	1	1	1	1	1
CO	132,764	75,240	49,507	51,238	53,240	48,229	46,413
Mobile Fossil Fuel Combustion	119,360	58,615	39,475	38,305	36,491	34,676	32,861
Forest Fires	2,792	8,515	2,845	5,683	9,499	6,298	6,298
Stationary Fossil Fuel Combustion	5,000	4,648	4,103	4,170	4,170	4,170	4,169
Industrial Processes and Product Use	4,129	1,557	1,280	1,229	1,229	1,229	1,229
Waste Combustion	978	1,403	1,084	1,003	1,003	1,003	1,003
Oil and Gas Activities	302	318	487	610	610	610	610
Agricultural Burning	202	177	229	233	234	238	238
Waste	1	7	5	5	5	5	5
NMVOCS	20,930	13,154	11,641	11,726	11,416	11,107	10,796
Industrial Processes and Product Use	7,638	5,849	4,133	3,929	3,929	3,929	3,928
Mobile Fossil Fuel Combustion	10,932	5,724	4,591	4,562	4,252	3,942	3,632
Oil and Gas Activities	554	510	2,205	2,517	2,517	2,517	2,517
Stationary Fossil Fuel Combustion	912	716	576	599	599	599	599
Waste Combustion	222	241	92	81	81	81	81
Waste	673	114	44	38	38	38	39
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA
SO₂	20,935	13,196	7,014	5,877	4,711	4,625	4,528
Stationary Fossil Fuel Combustion	18,407	11,541	6,120	5,008	3,859	3,790	3,710
Industrial Processes and Product Use	1,307	831	617	604	604	604	604
Mobile Fossil Fuel Combustion	390	180	117	108	108	108	108
Oil and Gas Activities	793	619	144	142	125	108	90
Waste Combustion	38	25	16	15	15	15	15
Waste	+	1	+	+	+	+	+
Agricultural Burning	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA - Not Available

Note: Totals may not sum due to independent rounding.

Source: (EPA 2015) except for estimates from Field Burning of Agricultural Residues.

⁸ NO_x and CO emission estimates from Field Burning of Agricultural Residues were estimated separately, and therefore not taken from EPA (2015).

Box 2-3: Sources and Effects of Sulfur Dioxide

Sulfur dioxide (SO_2) 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 2001). However, because SO_2 is short-lived and unevenly distributed in the atmosphere, its radiative forcing impacts are highly uncertain.

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 SO_2 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 SO_2 emissions in the Clean Air Act.

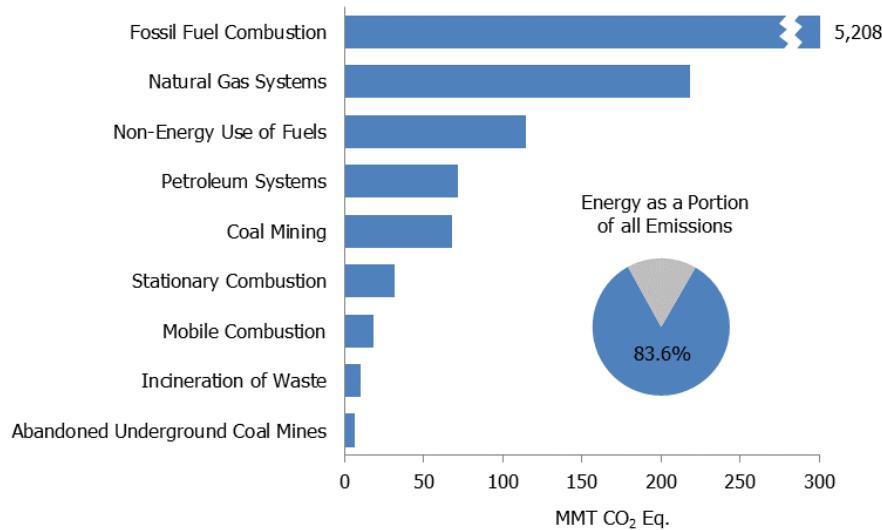
Electricity generation is the largest anthropogenic source of SO_2 emissions in the United States, accounting for 64.0 percent in 2014. Coal combustion contributes nearly all of those emissions (approximately 92 percent). Sulfur dioxide emissions have decreased in recent years, primarily as a result 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 83.6 percent of total greenhouse gas emissions on a carbon dioxide (CO₂) equivalent basis in 2014.¹ This included 97, 45, and 10 percent of the nation's CO₂, methane (CH₄), and nitrous oxide (N₂O) emissions, respectively. Energy-related CO₂ emissions alone constituted 78.3 percent of national emissions from all sources on a CO₂ equivalent basis, while the non-CO₂ emissions from energy-related activities represented a much smaller portion of total national emissions (5.4 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO₂ being the primary gas emitted (see Figure 3-1). Globally, approximately 32,190 million metric tons (MMT) of CO₂ were added to the atmosphere through the combustion of fossil fuels in 2013, of which the United States accounted for approximately 16 percent.² Due to their relative importance, fossil fuel combustion-related CO₂ emissions are considered separately, and in more detail than other energy-related emissions (see Figure 3-2). Fossil fuel combustion also emits CH₄ and N₂O. Stationary combustion of fossil fuels was the second-largest source of N₂O emissions in the United States and mobile fossil fuel combustion was the fourth-largest source.

Figure 3-1: 2014 Energy Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)

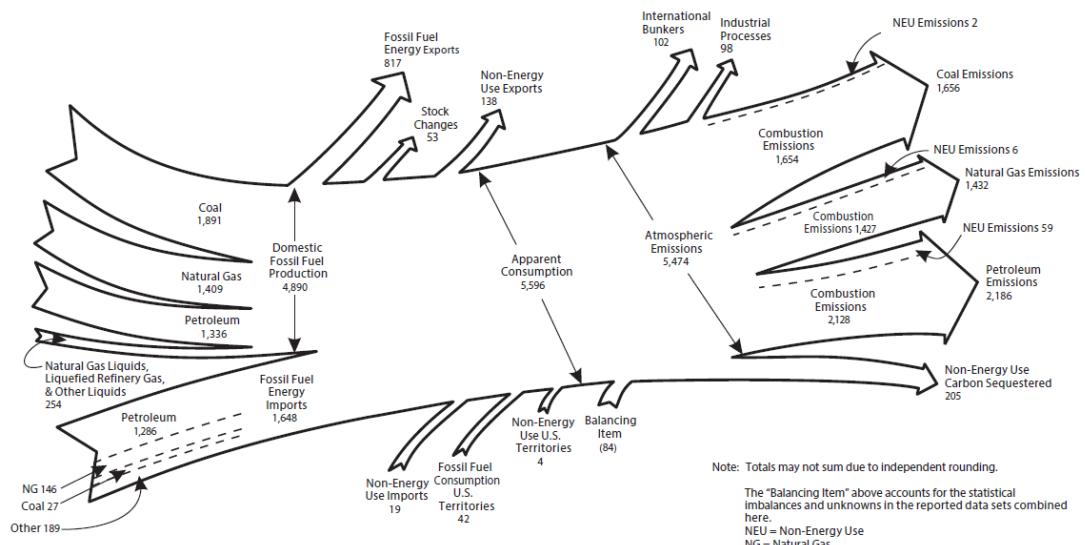


¹ Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO₂ Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

² Global CO₂ emissions from fossil fuel combustion were taken from International Energy Agency *CO₂ Emissions from Fossil Fuels Combustion – Highlights*

<<https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015.pdf>> IEA (2015).

Figure 3-2: 2014 U.S. Fossil Carbon Flows (MMT CO₂ Eq.)



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 CH₄ from natural gas systems, petroleum systems, and coal mining. Table 3-1 summarizes emissions from the Energy sector in units of MMT CO₂ Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 5,746.2 MMT CO₂ Eq. in 2014,³ an increase of 7.9 percent since 1990.

Table 3-1: CO₂, CH₄, and N₂O Emissions from Energy (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	4,908.8	5,932.5	5,520.0	5,386.6	5,179.7	5,330.8	5,377.9
Fossil Fuel Combustion	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
Electricity Generation	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3
Transportation	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6
Industrial	842.5	828.0	775.5	773.3	782.9	812.2	813.3
Residential	338.3	357.8	334.6	326.8	282.5	329.7	345.1
Commercial	217.4	223.5	220.1	220.7	196.7	221.0	231.9
U.S. Territories	27.9	49.9	41.4	41.5	43.6	43.5	41.0
Non-Energy Use of Fuels	118.1	138.9	114.1	108.5	105.6	121.7	114.3
Natural Gas Systems	37.7	30.1	32.4	35.7	35.2	38.5	42.4
Incineration of Waste	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Petroleum Systems	3.6	3.9	4.2	4.2	3.9	3.7	3.6
Biomass-Wood ^a	215.2	206.9	192.5	195.2	194.9	211.6	217.7
International Bunker Fuels ^a	103.5	113.1	117.0	111.7	105.8	99.8	103.2
Biomass-Ethanol ^a	4.2	22.9	72.6	72.9	72.8	74.7	76.1
CH₄	363.3	307.0	318.5	313.3	312.5	321.2	328.3
Natural Gas Systems	206.8	177.3	166.2	170.1	172.6	175.6	176.1
Petroleum Systems	38.7	48.8	54.1	56.3	58.4	64.7	68.1
Coal Mining	96.5	64.1	82.3	71.2	66.5	64.6	67.6
Stationary Combustion	8.5	7.4	7.1	7.1	6.6	8.0	8.1
Abandoned Underground Coal Mines	7.2	6.6	6.6	6.4	6.2	6.2	6.3
Mobile Combustion	5.6	2.7	2.3	2.2	2.2	2.1	2.0
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels ^a	0.2	0.1	0.1	0.1	0.1	0.1	0.1

³ Following the revised reporting requirements under the UNFCCC, this Inventory report presents CO₂ equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

N₂O	53.6	55.0	46.1	44.0	41.7	41.4	40.0
Stationary Combustion	11.9	20.2	22.2	21.3	21.4	22.9	23.4
Mobile Combustion	41.2	34.4	23.6	22.4	20.0	18.2	16.3
Incineration of Waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
<i>International Bunker Fuels^a</i>	0.9	1.0	1.0	1.0	0.9	0.9	0.9
Total	5,324.9	6,294.5	5,884.6	5,744.0	5,533.9	5,693.5	5,746.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^a These values are presented for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations, and are not included in the specific energy sector contribution to the totals, and are already accounted for elsewhere.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO₂, CH₄, and N₂O Emissions from Energy (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	4,908,041	5,932,474	5,519,975	5,386,609	5,179,749	5,330,837	5,377,857
Fossil Fuel Combustion	4,740,671	5,747,142	5,358,292	5,227,690	5,024,685	5,157,583	5,208,207
Non-Energy Use of Fuels	118,114	138,876	114,063	108,515	105,624	121,682	114,311
Natural Gas Systems	37,732	30,076	32,439	35,662	35,203	38,457	42,351
Incineration of Waste	7,972	12,454	11,026	10,550	10,362	9,421	9,421
Petroleum Systems	3,553	3,927	4,154	4,192	3,876	3,693	3,567
Biomass – Wood ^a	215,186	206,901	192,462	195,182	194,903	211,581	217,654
<i>International Bunker Fuels^a</i>	103,463	113,139	116,992	111,660	105,805	99,763	103,201
Biomass – Ethanol ^a	4,227	22,943	72,647	72,881	72,827	74,743	76,075
CH₄	14,532	12,281	12,741	12,533	12,498	12,848	13,132
Natural Gas Systems	8,270	7,093	6,647	6,803	6,906	7,023	7,045
Petroleum Systems	1,550	1,953	2,163	2,251	2,335	2,588	2,726
Coal Mining	3,860	2,565	3,293	2,849	2,658	2,584	2,703
Stationary Combustion	339	296	283	283	265	320	324
Abandoned Underground							
Coal Mines	288	264	263	257	249	249	253
Mobile Combustion	226	110	91	90	86	84	82
Incineration of Waste	+	+	+	+	+	+	+
<i>International Bunker Fuels^a</i>	7	5	6	5	4	3	3
N₂O	180	185	155	148	140	139	134
Stationary Combustion	40	68	74	71	72	77	79
Mobile Combustion	138	115	79	75	67	61	55
Incineration of Waste	2	1	1	1	1	1	1
<i>International Bunker Fuels^a</i>	3	3	3	3	3	3	3

+ Does not exceed 0.5 kt

^a These values are presented for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations, and are not included in the specific energy sector contribution to the totals, and are already accounted for elsewhere.

Note: Totals may not sum due to independent rounding.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

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 sinks 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). Additionally, the calculated emissions and sinks 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 sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this inventory report are comparable to emissions and sinks reported by other countries. Emissions and sinks provided in this Inventory do not preclude alternative examinations, but rather, this Inventory presents emissions and sinks 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 IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

Box 3-2: Energy Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as the Greenhouse Gas Reporting Program (GHGRP). 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO₂ underground for sequestration or other reasons. Reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. 40 CFR part 98 requires reporting by 41 industrial categories. Data reporting by affected facilities included the reporting of emissions from fuel combustion at that affected facility. In general, the threshold for reporting is 25,000 metric tons or more of CO₂ Eq. per year.

The GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this Inventory (see, also, Box 3-4). 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. 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. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the GHGRP website.

EPA presents the data collected by its GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.

3.1 Fossil Fuel Combustion (IPCC Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the gases CO₂, CH₄, and N₂O. Given that CO₂ is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO₂ emissions from fossil fuel combustion are discussed at the beginning of this section. Following that is a discussion of emissions of all three gases from fossil fuel combustion presented by sectoral breakdowns. Methodologies for estimating CO₂ from fossil fuel combustion also differ from the estimation of CH₄ and N₂O 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 CO₂, CH₄, and N₂O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO₂, CH₄, and N₂O Emissions from Fossil Fuel Combustion (MMT CO₂ Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2
CH ₄	14.1	10.2	9.3	9.3	8.8	10.1	10.1
N ₂ O	53.1	54.7	45.8	43.8	41.5	41.2	39.8
Total	4,807.9	5,812.0	5,413.4	5,280.8	5,074.9	5,208.8	5,258.1

Note: Totals may not sum due to independent rounding

Table 3-4: CO₂, CH₄, and N₂O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	4,740,671	5,747,142	5,358,292	5,227,690	5,024,685	5,157,583	5,208,207
CH ₄	565	406	372	374	352	404	405
N ₂ O	178	183	154	147	139	138	133

CO₂ 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. CO₂ emissions from fossil fuel combustion are presented in Table 3-5. In 2014, CO₂ emissions from fossil fuel combustion increased by 1.0 percent relative to the previous year. The increase in CO₂ emissions from fossil fuel combustion was a result of multiple factors, including: (1) colder winter conditions in the first quarter of 2014 resulting in an increased demand for heating fuel in the residential and commercial sectors; (2) an increase in transportation emissions resulting from an increase in vehicle miles traveled (VMT) and fuel use across on-road transportation modes; and (3) an increase in industrial production across multiple sectors resulting in slight increases in industrial sector emissions.⁴ In 2014, CO₂ emissions from fossil fuel combustion were 5,208.2 MMT CO₂ Eq., or 9.9 percent above emissions in 1990 (see Table 3-5).⁵

Table 3-5: CO₂ Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO₂ Eq.)

Fuel/Sector	1990	2005	2010	2011	2012	2013	2014
Coal	1,718.4	2,112.3	1,927.7	1,813.9	1,592.8	1,654.4	1,653.7
Residential	3.0	0.8	NO	NO	NO	NO	NO
Commercial	12.0	9.3	6.6	5.8	4.1	3.9	4.5
Industrial	155.3	115.3	90.1	82.0	74.1	75.7	75.3
Transportation	NE						
Electricity Generation	1,547.6	1,983.8	1,827.6	1,722.7	1,511.2	1,571.3	1,570.4
U.S. Territories	0.6	3.0	3.4	3.4	3.4	3.4	3.4
Natural Gas	1,000.3	1,166.7	1,272.1	1,291.5	1,352.6	1,391.2	1,426.6
Residential	238.0	262.2	258.6	254.7	224.8	266.2	277.6
Commercial	142.1	162.9	167.7	170.5	156.9	179.1	189.2
Industrial	408.9	388.5	407.2	417.3	434.8	451.9	466.0
Transportation	36.0	33.1	38.1	38.9	41.3	47.0	47.6
Electricity Generation	175.3	318.8	399.0	408.8	492.2	444.0	443.2
U.S. Territories	NO	1.3	1.5	1.4	2.6	3.0	3.0
Petroleum	2,021.5	2,467.8	2,158.2	2,121.9	2,078.9	2,111.6	2,127.5
Residential	97.4	94.9	76.0	72.2	57.7	63.4	67.5
Commercial	63.3	51.3	45.8	44.5	35.7	38.0	38.2
Industrial	278.3	324.2	278.2	274.0	274.1	284.6	271.9
Transportation	1,457.7	1,854.0	1,690.2	1,668.8	1,655.4	1,666.0	1,690.0
Electricity Generation	97.5	97.9	31.4	25.8	18.3	22.4	25.3
U.S. Territories	27.2	45.6	36.5	36.7	37.6	37.1	34.6
Geothermal^a	0.4						
Total	4,740.7	5,747.1	5,358.3	5,227.7	5,024.7	5,157.6	5,208.2

+ Does not exceed 0.05 MMT CO₂ Eq.

NE (Not estimated)

⁴ Further details on industrial sector combustion emissions are provided by EPA's GHGRP <<http://ghgdata.epa.gov/ghgp/main.do>>.

⁵ An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions Chapter.

NO (Not occurring)

^a Although not technically a fossil fuel, geothermal energy-related CO₂ emissions are included for reporting purposes.

Note: Totals may not sum due to independent rounding.

Trends in CO₂ 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 consumption patterns, however, tend to be more a function of aggregate societal trends that affect the scale of consumption (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, 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.⁶ Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO₂ Emissions and Total 2014 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO₂ Eq. and Percent)

Sector	Fuel Type	2010 to 2011	2011 to 2012	2012 to 2013	2013 to 2014	Total 2014
Electricity Generation	Coal	-104.9 -5.7%	-211.5 -12.3%	60.1 4.0%	-0.9 -0.1%	1,570.4
Electricity Generation	Natural Gas	9.8 2.5%	83.5 20.4%	-48.3 -9.8%	-0.8 -0.2%	443.2
Electricity Generation	Petroleum	-5.6 -17.8%	-7.5 -29.0%	4.1 22.3%	2.9 12.8%	25.3
Transportation ^a	Petroleum	-21.4 -1.3%	-13.3 -0.8%	10.6 0.6%	24.0 1.4%	1,690.0
Residential	Natural Gas	-3.9 -1.5%	-29.8 -11.7%	41.4 18.4%	11.4 4.3%	277.6
Commercial	Natural Gas	2.7 1.6%	-13.6 -8.0%	22.3 14.2%	10.0 5.6%	189.2
Industrial	Coal	-8.1 -9.0%	-7.9 -9.7%	1.7 2.3%	-0.4 -0.6%	75.3
Industrial	Natural Gas	10.1 2.5%	17.5 4.2%	17.1 3.9%	14.2 3.1%	466.0
All Sectors ^b	All Fuels ^b	-130.6 -2.4%	-203.0 -3.9%	132.9 2.6%	50.6 1.0%	5,208.2

^a Excludes emissions from International Bunker Fuels.

^b Includes fuels and sectors not shown in table.

Note: Totals may not sum due to independent rounding.

In the United States, 82 percent of the energy consumed in 2014 was produced through the combustion of fossil fuels such as coal, natural gas, and petroleum (see Figure 3-3 and Figure 3-4). The remaining portion was supplied by nuclear electric power (8 percent) and by a variety of renewable energy sources (10 percent), primarily hydroelectric power, wind energy and biofuels (EIA 2016).⁷ Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 35 percent of total U.S. energy consumption in 2014. Natural gas and coal followed in order of energy demand importance, accounting for approximately 28 percent and 19 percent of total U.S. energy consumption, respectively. Petroleum was consumed primarily in the transportation end-use sector and the vast majority of coal was used in electricity generation. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5) (EIA 2016).

⁶ Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States.

⁷ 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 3-3: 2014 U.S. Energy Consumption by Energy Source (Percent)

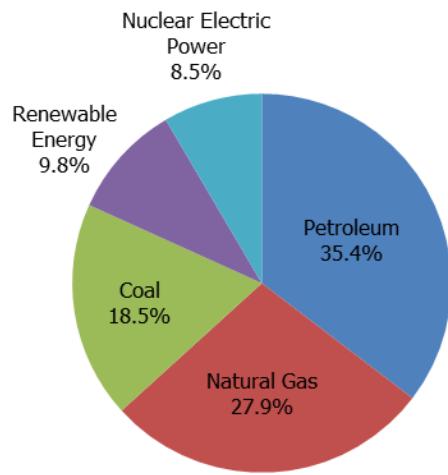


Figure 3-4: U.S. Energy Consumption (Quadrillion Btu)

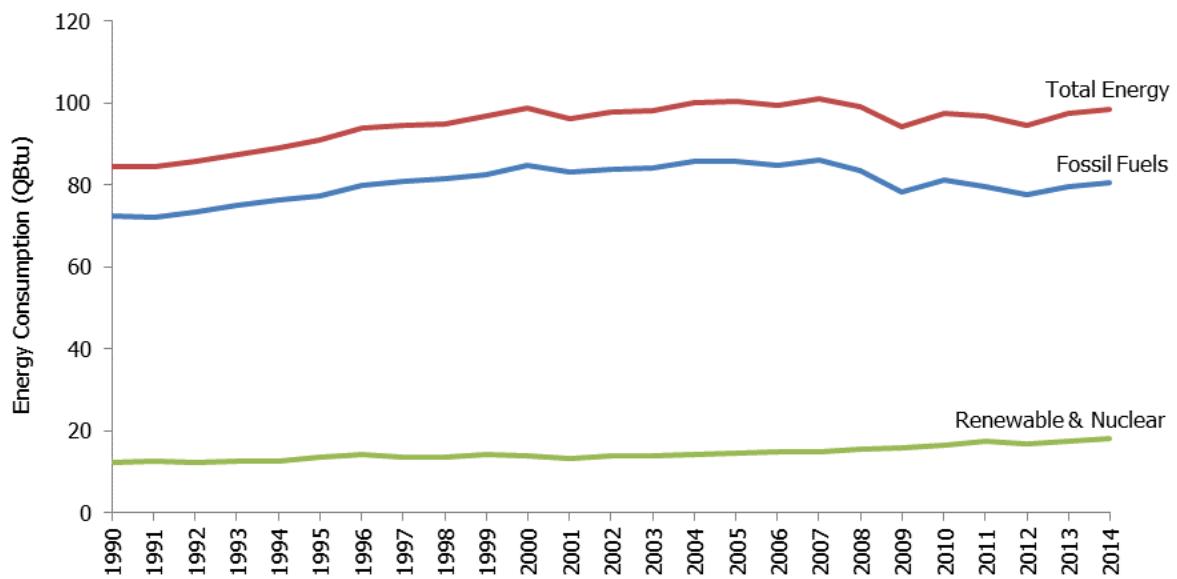
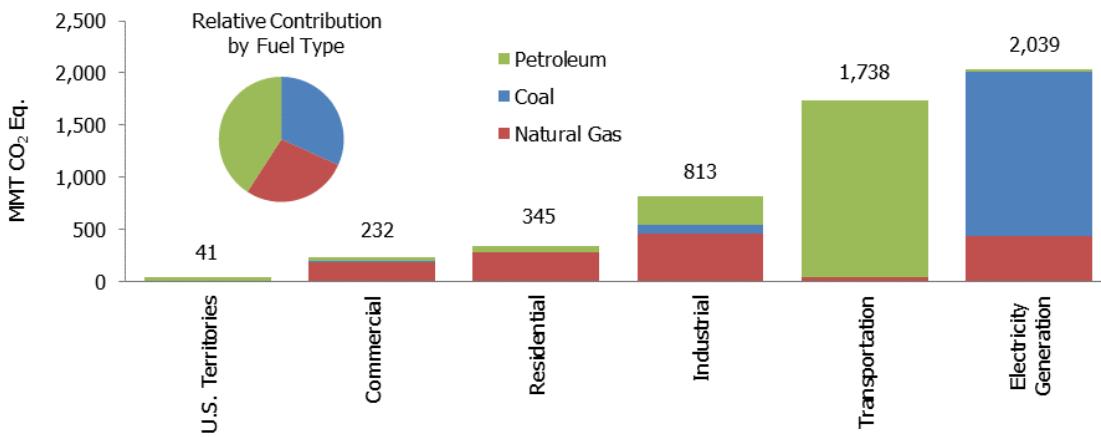


Figure 3-5: 2014 CO₂ Emissions from Fossil Fuel Combustion by Sector and Fuel Type (MMT CO₂ Eq.)



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 CO₂ and smaller amounts of other gases, including CH₄, CO, and NMVOCs.⁸ These other C containing non-CO₂ gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO₂ in the atmosphere. Therefore, it is assumed all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO₂.

Box 3-3: Weather and Non-Fossil Energy Effects on CO₂ from Fossil Fuel Combustion Trends

In 2014, weather conditions, and a very cold first quarter of the year in particular, caused a significant increase in energy demand for heating fuels and is reflected in the increased residential emissions during the early part of the year (EIA 2016). The United States in 2014 also experienced a cooler winter overall compared to 2013, as heating degree days increased (1.9 percent). Cooling degree days decreased by 0.6 percent and despite this decrease in cooling degree days, electricity demand to cool homes still increased slightly. Colder winter conditions compared to 2013 resulted in a significant increase in the amount of energy required for heating, and heating degree days in the United States were 0.6 percent above normal for the first time since 2003 (see Figure 3-6). Summer conditions were slightly cooler in 2014 compared to 2013, and summer temperatures were warmer than normal, with cooling degree days 6.7 percent above normal (see Figure 3-7) (EIA 2016).⁹

⁸ See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO₂ gas emissions from fossil fuel combustion.

⁹ 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 1971 through 2000. The variation in these normals during this time period was ±10 percent and ±14 percent for heating and cooling degree days, respectively (99 percent confidence interval).

Figure 3-6: Annual Deviations from Normal Heating Degree Days for the United States (1950–2014, Index Normal = 100)

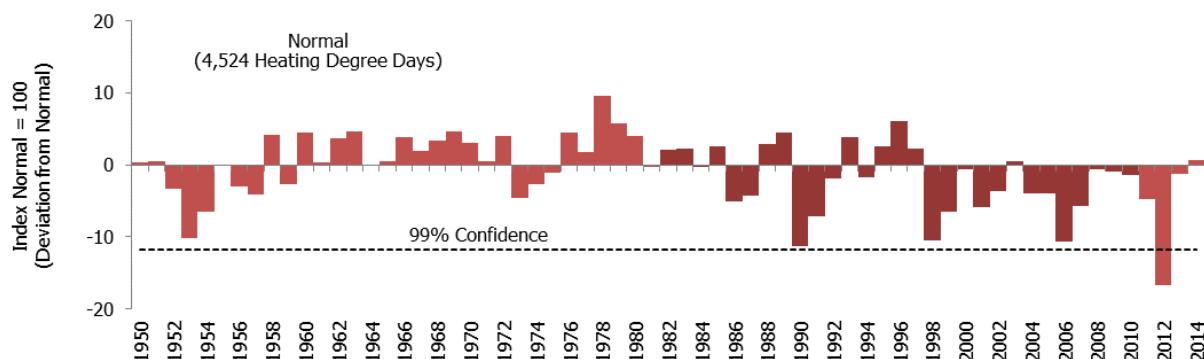
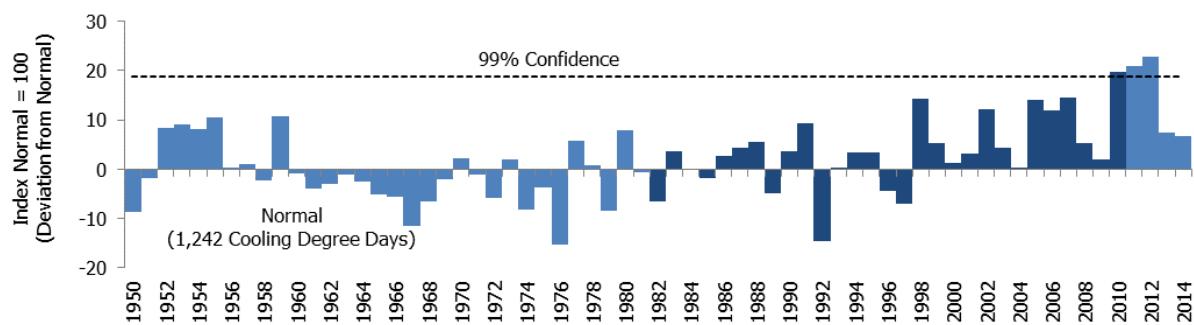


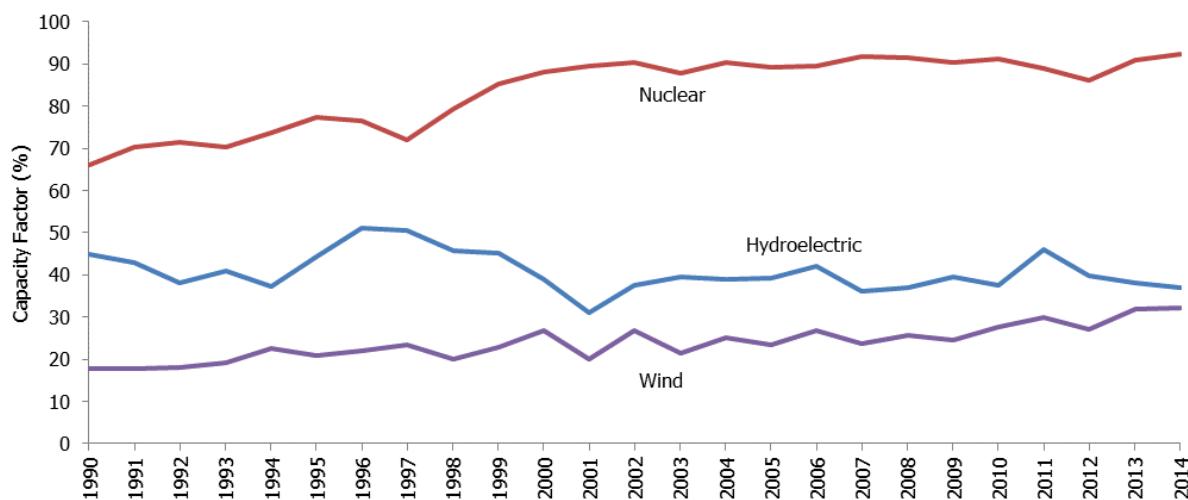
Figure 3-7: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2014, Index Normal = 100)



Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors)¹⁰ of existing plants in 2014 remained high at 92 percent. Electricity output by hydroelectric power plants decreased in 2014 by approximately 3 percent. In recent years, the wind power sector has been showing strong growth, such that, on the margin, it is becoming a relatively important electricity source. Electricity generated by nuclear plants in 2014 provided more than 3 times as much of the energy generated in the United States from hydroelectric plants (EIA 2016). Nuclear, hydroelectric, and wind power capacity factors since 1990 are shown in Figure 3-8.

¹⁰ 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 (2016).

Figure 3-8: Nuclear, Hydroelectric, and Wind Power Plant Capacity Factors in the United States (1990–2014, Percent)



Fossil Fuel Combustion Emissions by Sector

In addition to the CO₂ emitted from fossil fuel combustion, CH₄ and N₂O are emitted from stationary and mobile combustion as well. Table 3-7 provides an overview of the CO₂, CH₄, and N₂O emissions from fossil fuel combustion by sector.

Table 3-7: CO₂, CH₄, and N₂O Emissions from Fossil Fuel Combustion by Sector (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Electricity Generation	1,828.5	2,417.4	2,277.4	2,175.8	2,040.5	2,057.7	2,059.4
CO ₂	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3
CH ₄	0.3	0.5	0.5	0.4	0.4	0.4	0.4
N ₂ O	7.4	16.0	18.5	17.6	17.8	19.1	19.6
Transportation	1,540.6	1,924.1	1,754.2	1,732.3	1,718.9	1,733.3	1,756.0
CO ₂	1,493.8	1,887.0	1,728.3	1,707.6	1,696.8	1,713.0	1,737.6
CH ₄	5.6	2.7	2.3	2.2	2.2	2.1	2.0
N ₂ O	41.2	34.4	23.6	22.4	20.0	18.2	16.3
Industrial	847.4	832.7	779.3	777.3	786.9	816.2	817.2
CO ₂	842.5	828.0	775.5	773.3	782.9	812.2	813.3
CH ₄	1.8	1.7	1.4	1.5	1.5	1.5	1.5
N ₂ O	3.1	2.9	2.4	2.5	2.5	2.4	2.4
Residential	344.6	362.8	339.4	331.7	287.0	335.6	351.1
CO ₂	338.3	357.8	334.6	326.8	282.5	329.7	345.1
CH ₄	5.2	4.1	4.0	4.0	3.7	5.0	5.0
N ₂ O	1.0	0.9	0.8	0.8	0.7	1.0	1.0
Commercial	218.8	224.9	221.5	222.1	197.9	222.4	233.3
CO ₂	217.4	223.5	220.1	220.7	196.7	221.0	231.9
CH ₄	1.0	1.1	1.1	1.0	0.9	1.0	1.1
N ₂ O	0.4	0.3	0.3	0.3	0.3	0.3	0.3

U.S. Territories^a	28.0	50.1	41.6	41.7	43.7	43.7	41.2
Total	4,807.9	5,812.0	5,413.4	5,280.8	5,074.9	5,208.8	5,258.1

^a U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

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

Other than CO₂, gases emitted from stationary combustion include the greenhouse gases CH₄ and N₂O and the indirect greenhouse gases NO_x, CO, and NMVOCs.¹¹ Methane and N₂O emissions from stationary combustion sources depend upon fuel characteristics, size and vintage, 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 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 CH₄ content of the fuel and combustion efficiency.

Mobile combustion produces greenhouse gases other than CO₂, including CH₄, N₂O, and indirect greenhouse gases including NO_x, CO, and NMVOCs. As with stationary combustion, N₂O 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. N₂O 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 idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH₄ 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 electricity generation to the sectors in which it is used. Four end-use sectors were defined: industrial, transportation, residential, and commercial. In the table below, electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption, with the exception of CH₄ and N₂O from transportation.¹² Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data. This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity consumption in that sector. The results of this alternative method are presented in Table 3-8.

Table 3-8: CO₂, CH₄, and N₂O Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation	1,543.7	1,928.9	1,758.7	1,736.6	1,722.8	1,737.4	1,760.1
CO ₂	1,496.8	1,891.8	1,732.7	1,711.9	1,700.6	1,717.0	1,741.7
CH ₄	5.6	2.7	2.3	2.2	2.2	2.1	2.0
N ₂ O	41.2	34.4	23.7	22.5	20.1	18.2	16.4
Industrial	1,537.0	1,574.3	1,425.7	1,407.2	1,385.0	1,416.6	1,416.6
CO ₂	1,529.2	1,564.6	1,416.5	1,398.0	1,375.7	1,407.0	1,406.8
CH ₄	2.0	1.9	1.6	1.6	1.6	1.6	1.6
N ₂ O	5.9	7.8	7.6	7.6	7.7	8.0	8.2
Residential	940.2	1,224.9	1,186.5	1,129.0	1,018.8	1,077.6	1,093.6
CO ₂	931.4	1,214.1	1,174.6	1,117.5	1,007.8	1,064.6	1,080.3
CH ₄	5.4	4.2	4.2	4.2	3.9	5.1	5.2
N ₂ O	3.4	6.6	7.7	7.3	7.1	7.9	8.1

¹¹ Sulfur dioxide (SO₂) emissions from stationary combustion are addressed in Annex 6.3.

¹² Separate calculations were performed for transportation-related CH₄ and N₂O. The methodology used to calculate these emissions are discussed in the mobile combustion section.

Commercial	759.1	1,033.7	1,000.9	966.3	904.5	933.6	946.7
CO ₂	755.4	1,026.8	993.0	958.8	897.0	925.5	938.4
CH ₄	1.1	1.2	1.2	1.2	1.1	1.2	1.2
N ₂ O	2.5	5.7	6.6	6.3	6.4	6.9	7.1
U.S. Territories^a	28.0	50.1	41.6	41.7	43.7	43.7	41.2
Total	4,807.9	5,812.0	5,413.4	5,280.8	5,074.9	5,208.8	5,258.1

^a U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

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

Stationary Combustion

The direct combustion of fuels by stationary sources in the electricity generation, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-9 presents CO₂ emissions from fossil fuel combustion by stationary sources. The CO₂ emitted is closely linked to the type of fuel being combusted in each sector (see Methodology section of CO₂ from Fossil Fuel Combustion). Other than CO₂, gases emitted from stationary combustion include the greenhouse gases CH₄ and N₂O. Table 3-10 and Table 3-11 present CH₄ and N₂O emissions from the combustion of fuels in stationary sources.¹³ Methane and N₂O emissions from stationary combustion sources depend upon fuel characteristics, 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 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 CH₄ content of the fuel and combustion efficiency. The CH₄ and N₂O emission estimation methodology was revised in 2010 to utilize the facility-specific technology and fuel use data reported to EPA's Acid Rain Program (see Methodology section for CH₄ and N₂O from stationary combustion). Please refer to Table 3-7 for the corresponding presentation of all direct emission sources of fuel combustion.

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

Sector/Fuel Type	1990	2005	2010	2011	2012	2013	2014
Electricity Generation	1,820.8	2,400.9	2,258.4	2,157.7	2,022.2	2,038.1	2,039.3
Coal	1,547.6	1,983.8	1,827.6	1,722.7	1,511.2	1,571.3	1,570.4
Natural Gas	175.3	318.8	399.0	408.8	492.2	444.0	443.2
Fuel Oil	97.5	97.9	31.4	25.8	18.3	22.4	25.3
Geothermal	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Industrial	842.5	828.0	775.5	773.3	782.9	812.2	813.3
Coal	155.3	115.3	90.1	82.0	74.1	75.7	75.3
Natural Gas	408.9	388.5	407.2	417.3	434.8	451.9	466.0
Fuel Oil	278.3	324.2	278.2	274.0	274.1	284.6	271.9
Commercial	217.4	223.5	220.1	220.7	196.7	221.0	231.9
Coal	12.0	9.3	6.6	5.8	4.1	3.9	4.5
Natural Gas	142.1	162.9	167.7	170.5	156.9	179.1	189.2
Fuel Oil	63.3	51.3	45.8	44.5	35.7	38.0	38.2
Residential	338.3	357.8	334.6	326.8	282.5	329.7	345.1
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	238.0	262.2	258.6	254.7	224.8	266.2	277.6
Fuel Oil	97.4	94.9	76.0	72.2	57.7	63.4	67.5
U.S. Territories	27.9	49.9	41.4	41.5	43.6	43.5	41.0

¹³ Since emission estimates for U.S. Territories cannot be disaggregated by gas in Table 3-10 and Table 3-11, the values for CH₄ and N₂O exclude U.S. territory emissions.

Coal	0.6	3.0	3.4	3.4	3.4	3.4	3.4
Natural Gas	NO	1.3	1.5	1.4	2.6	3.0	3.0
Fuel Oil	27.2	45.6	36.5	36.7	37.6	37.1	34.6
Total	3,246.9	3,860.1	3,630.0	3,520.1	3,327.9	3,444.6	3,470.6

+ Does not exceed 0.05 MMT CO₂ Eq.

NO - Not occurring

Note: Totals may not sum due to independent rounding.

Table 3-10: CH₄ Emissions from Stationary Combustion (MMT CO₂ Eq.)

Sector/Fuel Type	1990	2005	2010	2011	2012	2013	2014
Electric Power	0.3	0.5	0.5	0.4	0.4	0.4	0.4
Coal	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Wood	+	+	+	+	+	+	+
Industrial	1.8	1.7	1.5	1.5	1.5	1.5	1.5
Coal	0.4	0.3	0.2	0.2	0.2	0.2	0.2
Fuel Oil	0.2	0.2	0.2	0.1	0.1	0.2	0.1
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.0	1.0	0.9	0.9	1.0	0.9	0.9
Commercial	1.0	1.1	1.1	1.0	0.9	1.0	1.1
Coal	+	+	+	+	+	+	+
Fuel Oil	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Natural gas	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Wood	0.5	0.5	0.5	0.5	0.4	0.5	0.5
Residential	5.2	4.1	4.0	4.0	3.7	5.0	5.0
Coal	0.2	0.1	NO	NO	NO	NO	NO
Fuel Oil	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Natural Gas	0.5	0.6	0.6	0.6	0.5	0.6	0.6
Wood	4.1	3.1	3.1	3.2	3.0	4.1	4.1
U.S. Territories	+	0.1	0.1	0.1	0.1	0.1	0.1
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	NO	+	+	+	+	+	+
Wood	NO						
Total	8.5	7.4	7.1	7.1	6.6	8.0	8.1

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 3-11: N₂O Emissions from Stationary Combustion (MMT CO₂ Eq.)

Sector/Fuel Type	1990	2005	2010	2011	2012	2013	2014
Electricity Generation	7.4	16.0	18.5	17.6	17.8	19.1	19.6
Coal	6.3	11.6	12.5	11.5	10.2	12.1	12.4
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	1.0	4.3	5.9	6.1	7.5	7.0	7.2
Wood	+	+	+	+	+	+	+
Industrial	3.1	2.9	2.5	2.4	2.4	2.4	2.4
Coal	0.7	0.5	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.5	0.5	0.4	0.4	0.3	0.4	0.3
Natural Gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.6	1.6	1.4	1.5	1.5	1.5	1.5
Commercial	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Coal	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	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	0.8	0.8	0.7	1.0	1.0
Coal	+	+	NO	NO	NO	NO	NO
Fuel Oil	0.2	0.2	0.2	0.2	0.2	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	0.5	0.5	0.5	0.7	0.7
U.S. Territories	0.1						
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	NO	+	+	+	+	+	+
Wood	NO						
Total	11.9	20.2	22.2	21.3	21.4	22.9	23.4

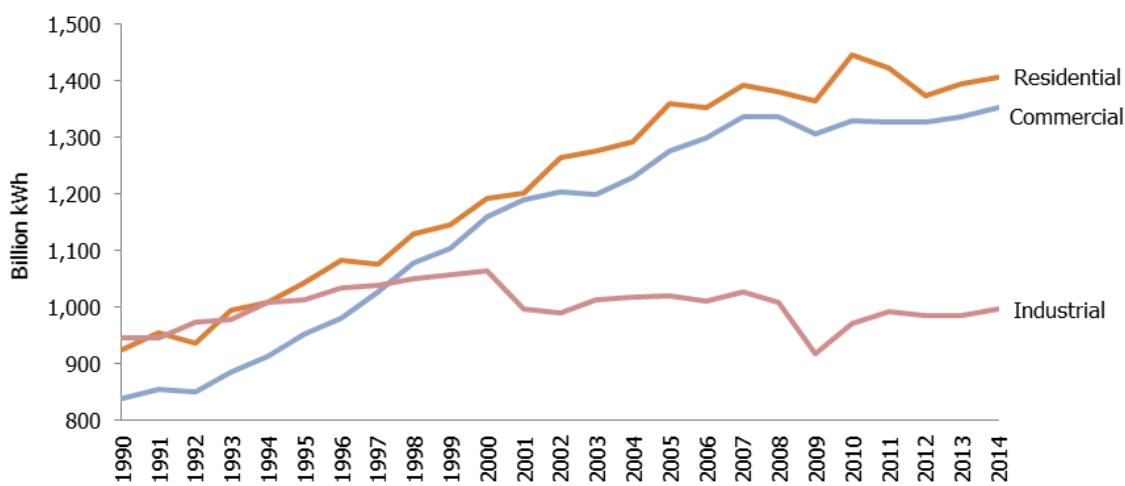
+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Electricity Generation

The process of generating electricity is the single largest source of CO₂ emissions in the United States, representing 37 percent of total CO₂ emissions from all CO₂ emissions sources across the United States. Methane and N₂O accounted for a small portion of emissions from electricity generation, representing less than 0.1 percent and 1.0 percent, respectively. Electricity generation also accounted for the largest share of CO₂ emissions from fossil fuel combustion, approximately 39.2 percent in 2014. Methane and N₂O from electricity generation represented 4.4 and 49.3 percent of total methane and N₂O emissions from fossil fuel combustion in 2014, respectively. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-9). Electricity generators, including those using low-CO₂ emitting technologies, relied on coal for approximately 39 percent of their total energy requirements in 2014. Recently an increase in the carbon intensity of fuels consumed to generate electricity has occurred due to an increase in coal consumption, and decreased natural gas consumption and other generation sources. Total U.S. electricity generators used natural gas for approximately 27 percent of their total energy requirements in 2014 (EIA 2015a).

Figure 3-9: Electricity Generation Retail Sales by End-Use Sector (Billion kWh)



The electric power industry includes all power producers, consisting of both regulated utilities and non-utilities (e.g. independent power producers, qualifying co-generators, and other small power producers). 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, while the other sectors consist of those producers that indicate their primary business is something other than the production of electricity.¹⁴

The industrial, residential, and commercial end-use sectors, as presented in Table 3-8, were reliant on electricity for meeting energy needs. The residential and commercial end-use sectors were especially reliant on electricity consumption for lighting, heating, air conditioning, and operating appliances. Electricity sales to the residential and commercial end-use sectors in 2014 increased approximately 0.9 percent and 1.1 percent, respectively. The trend in the residential and commercial sectors can largely be attributed to colder, more energy-intensive winter conditions compared to 2013. Electricity sales to the industrial sector in 2014 increased approximately 1.2 percent. Overall, in 2014, the amount of electricity generated (in kWh) increased approximately 1.1 percent relative to the previous year, while CO₂ emissions from the electric power sector increased by 0.1 percent. The increase in CO₂ emissions, despite the relatively larger increase in electricity generation was a result of a slight decrease in the consumption of coal and natural gas for electricity generation by 0.1 percent and 0.2 percent, respectively, in 2014, and an increase in the consumption of petroleum for electricity generation by 15.8 percent.

Industrial Sector

Industrial sector CO₂, CH₄, and N₂O, emissions accounted for 16, 15, and 6 percent of CO₂, CH₄, and N₂O, emissions from fossil fuel combustion, respectively. Carbon dioxide, CH₄, and N₂O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial sector, per the underlying energy consumption data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy consumption is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Paper, Primary Metals, Food, and Nonmetallic Mineral Products—represent the vast majority of the energy use (EIA 2016 and EIA 2009b).

In theory, emissions from the industrial sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions.¹⁵ In addition, 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) also have a significant effect on industrial emissions.

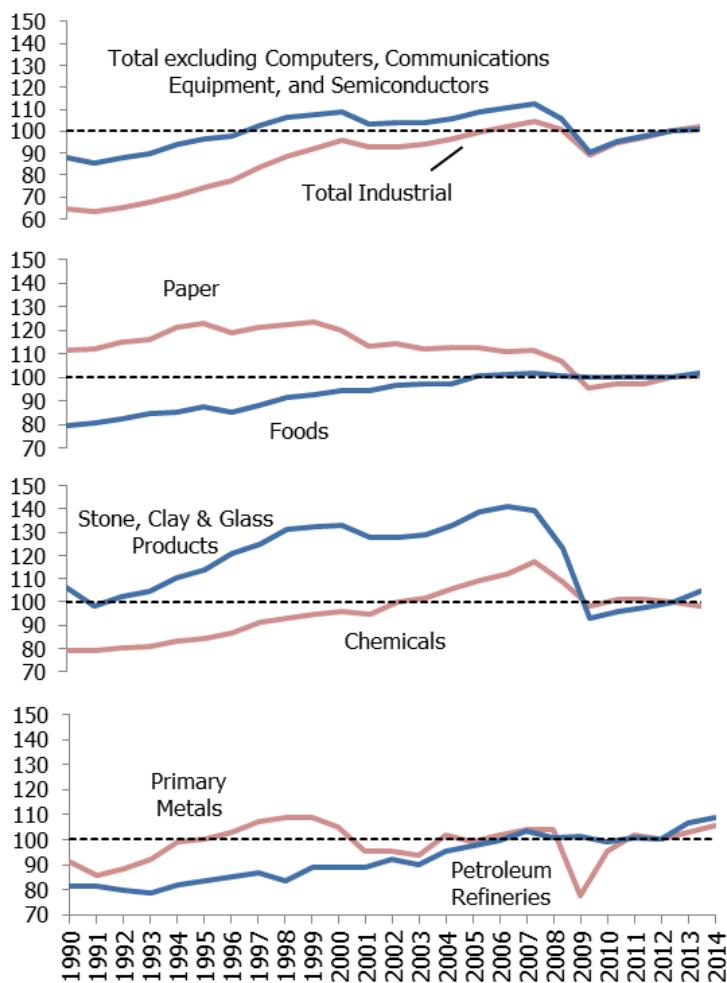
From 2013 to 2014, total industrial production and manufacturing output increased by 3.7 percent (FRB 2015). Over this period, output increased across production indices for Food, Petroleum Refineries, Chemicals, Primary Metals, and Nonmetallic Mineral Products, and decreased slightly for Paper (see Figure 3-10). Through EPA's Greenhouse Gas Reporting Program (GHGRP), industrial trends can be discerned from the overall EIA industrial fuel consumption data used for these calculations. For example, from 2013 to 2014 the underlying EIA data showed increased consumption of natural gas and a decrease in petroleum fuels in the industrial sector. EPA's GHGRP data highlights that chemical manufacturing and nonmetallic mineral products were contributors to these trends.¹⁶

¹⁴ Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Nonutilities produce electricity for their own use, to sell to large consumers, or to sell on the wholesale electricity market (e.g., to utilities for distribution and resale to customers).

¹⁵ 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.

¹⁶ Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See <<http://ghgdata.epa.gov/ghgp/main.do>>.

Figure 3-10: Industrial Production Indices (Index 2007=100)



Despite the growth in industrial output (64 percent) and the overall U.S. economy (78 percent) from 1990 to 2014, CO₂ emissions from fossil fuel combustion in the industrial sector decreased by 3.5 percent over the same time series. A number of factors are believed to have caused this disparity between growth in industrial output and decrease in industrial emissions, including: (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. In 2014, CO₂, CH₄, and N₂O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,416.6 MMT CO₂ Eq., or approximately equal to 2013 emissions.

Residential and Commercial Sectors

Residential and commercial sector CO₂ emissions accounted for 7 and 4 percent of CO₂ emissions from fossil fuel combustion, CH₄ emissions accounted for 49 and 11 percent of CH₄ emissions from fossil fuel combustion, and N₂O emissions accounted for 2 and 1 percent of N₂O 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. Coal consumption was a minor component of energy use in both of these end-use sectors. In 2014, CO₂, CH₄, and N₂O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,093.6 MMT CO₂ Eq. and 946.7 MMT CO₂ Eq., respectively. Total CO₂, CH₄, and N₂O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors increased by 1.5 and 1.4 percent from 2013 to 2014, respectively.

Emissions from the residential and commercial sectors have generally been increasing since 1990, and are often correlated with short-term fluctuations in energy consumption caused by weather conditions, rather than prevailing economic conditions. In the long-term, both sectors are also affected by population growth, regional migration trends, and changes in housing and building attributes (e.g., size and insulation).

In 2014, combustion emissions from natural gas consumption represent 80 and 82 percent of the direct fossil fuel CO₂ emissions from the residential and commercial sectors, respectively. Natural gas combustion CO₂ emissions from the residential and commercial sectors in 2014 increased by 4.3 percent and 5.6 percent from 2013 levels, 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 for CO₂ 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, CO₂, CH₄, and N₂O emissions are not presented for U.S. Territories in the tables above, though the emissions will include some 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 3-8. For direct emissions from transportation (i.e., not including emissions associated with the sector's electricity consumption), please see Table 3-7.

Transportation End-Use Sector

The transportation end-use sector accounted for 1,760.1 MMT CO₂ Eq. in 2014, which represented 33 percent of CO₂ emissions, 20 percent of CH₄ emissions, and 41 percent of N₂O emissions from fossil fuel combustion, respectively.¹⁷ Fuel purchased in the United States for international aircraft and marine travel accounted for an additional 104.2 MMT CO₂ Eq. in 2014; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols.

From 1990 to 2014, transportation emissions from fossil fuel combustion rose by 14 percent due, in large part, to increased demand for travel with limited gains in fuel efficiency for much of this time period. The number of vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased 37 percent from 1990 to 2014, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices.

From 2013 to 2014, CO₂ emissions from the transportation end-use sector increased by 1.4 percent.¹⁸ The increase in emissions can largely be attributed to small increases in VMT and fuel use across many on-road transportation modes. Commercial aircraft emissions have decreased 18 percent since 2007.¹⁹ 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 CO₂ from fossil fuel combustion, which increased by 16 percent from 1990 to

¹⁷ Note that these totals include CO₂, CH₄ and N₂O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH₄ and N₂O emissions from transportation rail electricity.

¹⁸ Note that this value does not include lubricants.

¹⁹ Commercial aircraft, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

2014. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO₂, N₂O, CH₄, and HFCs.

Transportation Fossil Fuel Combustion CO₂ Emissions

Domestic transportation CO₂ emissions increased by 16 percent (244.8 MMT CO₂) between 1990 and 2014, an annualized increase of 0.7 percent. Among domestic transportation sources, light-duty vehicles (including passenger cars and light-duty trucks) represented 60 percent of CO₂ emissions from fossil fuel combustion, medium- and heavy-duty trucks and buses 24 percent, commercial aircraft 7 percent, and other sources 9 percent. See Table 3-12 for a detailed breakdown of transportation CO₂ 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.²⁰ Ethanol consumption from the transportation sector has increased from 0.7 billion gallons in 1990 to 12.9 billion gallons in 2014, while biodiesel consumption has increased from 0.01 billion gallons in 2001 to 1.4 billion gallons in 2014. For further information, see the section on biofuel consumption at the end of this chapter and Table A-93 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,046.9 MMT CO₂ in 2014, an increase of 10 percent (96.4 MMT CO₂) from 1990 due, in large part, to increased demand for travel as fleetwide 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 2014). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,181.1 MMT CO₂ in 2004, and since then have declined about 11 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (Figure 3-11) 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, the rate of VMT growth slowed while average new vehicle fuel economy began to increase. Average new vehicle fuel economy has improved almost every year since 2005, and the truck share has decreased to about 41 percent of new vehicles in model year 2014 (EPA 2015a).

Medium- and heavy-duty truck CO₂ emissions increased by 75 percent from 1990 to 2014. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 94 percent between 1990 and 2014.²¹ Carbon dioxide from the domestic operation of commercial aircraft increased by 5 percent (5.3 MMT CO₂) from 1990 to 2014.²² Across all categories of aviation, excluding international bunkers, CO₂ emissions decreased by 20 percent (37.3 MMT CO₂) between 1990 and 2014.²³ This includes a 56 percent (19.6 MMT CO₂) decrease in CO₂ emissions from domestic military operations.

Transportation sources also produce CH₄ and N₂O; these emissions are included in Table 3-13 and Table 3-14 and in the “Mobile Combustion” Section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO₂, CH₄, N₂O, and HFCs.

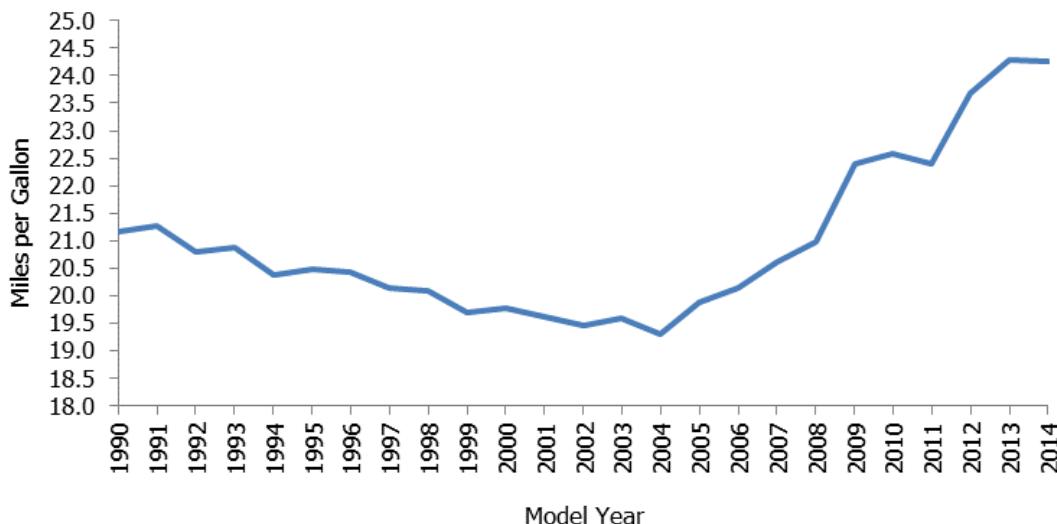
²⁰ Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA’s “Renewable Fuels: Regulations & Standards;” See <<http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm>>.

²¹ While FHWA data shows consistent growth in medium- and heavy-duty truck VMT over the 1990 to 2014 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 2014 time period. During the time period prior to the method change (1990-2006), VMT for medium- and heavy-duty trucks increased by 51 percent.

²² Commercial aircraft, as modeled in FAA’s AEDT, consists of passenger aircraft, cargo, and other chartered flights.

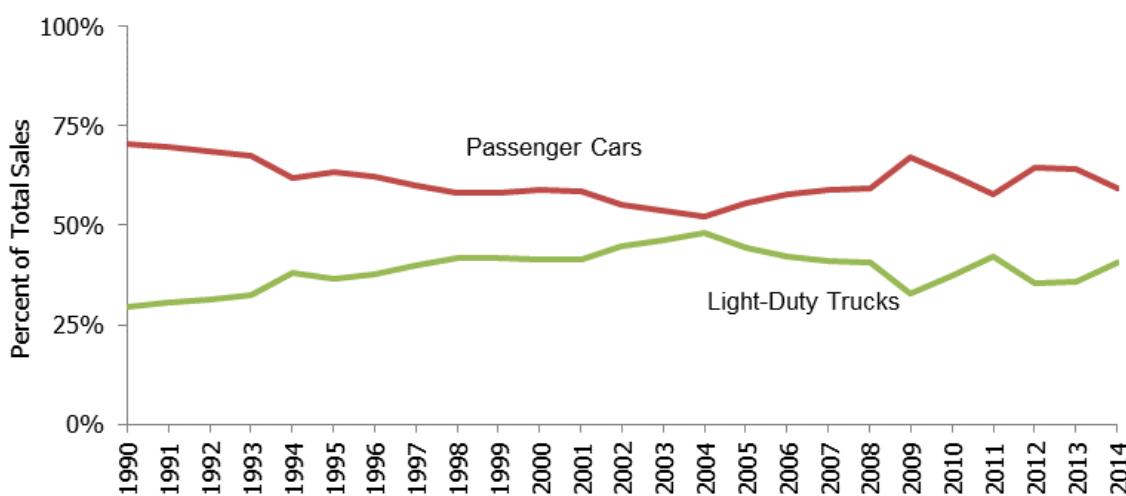
²³ Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-11: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2014 (miles/gallon)



Source: EPA (2015)

Figure 3-12: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2014 (Percent)



Source: EPA (2015)

Table 3-12: CO₂ Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO₂ Eq.)

Fuel/Vehicle Type	1990	2005	2010 ^a	2011	2012	2013	2014
Gasoline ^b	983.5	1,183.7	1,092.5	1,068.8	1,064.7	1,065.6	1,083.8
Passenger Cars	621.4	655.9	738.2	732.8	731.4	731.4	733.5
Light-Duty Trucks	309.1	477.2	295.0	280.4	277.4	277.7	293.5

Medium- and Heavy-Duty Trucks ^c	38.7	34.8	42.3	38.9	38.7	39.5	40.0
Buses	0.3	0.4	0.7	0.7	0.8	0.8	0.9
Motorcycles	1.7	1.6	3.6	3.6	4.1	3.9	3.8
Recreational Boats ^d	12.2	13.9	12.6	12.4	12.3	12.3	12.2
Distillate Fuel Oil (Diesel)^{b,e}	262.9	457.5	422.0	430.0	427.5	433.9	447.6
Passenger Cars	7.9	4.2	3.7	4.1	4.1	4.1	4.1
Light-Duty Trucks	11.5	25.8	12.5	13.0	12.9	12.9	13.9
Medium- and Heavy-Duty Trucks ^c	190.5	360.2	342.7	344.4	344.4	350.0	361.3
Buses	8.0	10.6	13.5	14.4	15.4	15.5	16.6
Rail	35.5	45.5	38.6	40.4	39.5	40.1	41.7
Recreational Boats	2.0	3.2	3.6	3.6	3.7	3.7	3.8
Ships and Other Boats ^f	7.5	8.0	7.4	10.1	7.5	7.5	6.2
<i>International Bunker Fuels^g</i>	<i>11.7</i>	<i>9.4</i>	<i>9.5</i>	<i>7.9</i>	<i>6.8</i>	<i>5.6</i>	<i>6.1</i>
Jet Fuel	184.2	189.3	151.5	146.6	143.4	147.1	148.6
Commercial Aircraft ^h	109.9	132.7	113.3	114.6	113.3	114.3	115.2
Military Aircraft	35.0	19.4	13.6	11.6	12.1	11.0	15.4
General Aviation Aircraft	39.4	37.3	24.6	20.4	18.0	21.8	18.0
<i>International Bunker Fuels^g</i>	<i>38.0</i>	<i>60.1</i>	<i>61.0</i>	<i>64.8</i>	<i>64.5</i>	<i>65.7</i>	<i>69.4</i>
<i>International Bunker Fuels from Commercial Aviation</i>	<i>30.0</i>	<i>55.6</i>	<i>57.4</i>	<i>61.7</i>	<i>61.4</i>	<i>62.8</i>	<i>66.3</i>
Aviation Gasoline	3.1	2.4	1.9	1.9	1.7	1.5	1.5
General Aviation Aircraft	3.1	2.4	1.9	1.9	1.7	1.5	1.5
Residual Fuel Oil	22.6	19.3	20.4	19.4	15.8	15.1	5.8
Ships and Other Boats ^f	22.6	19.3	20.4	19.4	15.8	15.1	5.8
<i>International Bunker Fuels^g</i>	<i>53.7</i>	<i>43.6</i>	<i>46.5</i>	<i>38.9</i>	<i>34.5</i>	<i>28.5</i>	<i>27.7</i>
Natural Gas	36.0	33.1	38.1	38.9	41.3	47.0	47.6
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Buses	+	0.8	1.1	1.1	1.0	1.1	1.1
Pipeline ⁱ	36.0	32.2	37.1	37.8	40.3	45.9	46.5
LPG	1.4	1.7	1.8	2.1	2.3	2.7	2.7
Light-Duty Trucks	0.6	1.3	1.3	1.5	1.6	1.9	1.9
Medium- and Heavy-Duty Trucks ^c	0.8	0.4	0.6	0.6	0.7	0.8	0.8
Buses	+	+	+	+	+	+	+
Electricity	3.0	4.7	4.5	4.3	3.9	4.0	4.1
Rail	3.0	4.7	4.5	4.3	3.9	4.0	4.1
Ethanol^j	4.1	22.4	71.3	71.5	71.5	73.4	74.8
Total	1,496.8	1,891.8	1,732.7	1,711.9	1,700.6	1,717.0	1,741.7
Total (Including Bunkers)^g	1,600.3	2,004.9	1,849.7	1,823.6	1,806.4	1,816.8	1,844.9

+ Does not exceed 0.05 MMT CO₂ 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 2014 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 VM-1 and MF-27 (FHWA 1996 through 2015). 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 2015). TEDB data for 2014 has not been published yet, therefore 2013 data is used as a proxy.

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

^d In 2015, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2014. This update resulted in small changes (less than two percent) to the 1999 through 2013 time series for NONROAD fuel consumption due to differences in the gasoline and diesel default fuel densities used within the model iterations.

^e Updates to the distillate fuel oil heat content data from EIA for years 1993 through 2014 resulted in changes to the time series for energy consumption and emissions compared to the previous Inventory.

^f Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

^g 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.

^h Commercial aircraft, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.

ⁱ Pipelines reflect CO₂ emissions from natural gas powered pipelines transporting natural gas.

^j Ethanol estimates are presented for informational purposes only. See Section 3.10 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.

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 CO₂ emissions from U.S. Territories, since these are covered in a separate chapter of the Inventory. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH₄ and N₂O Emissions

Mobile combustion includes emissions of CH₄ and N₂O from all transportation sources identified in the U.S. Inventory with the exception of pipelines and electric locomotives;²⁴ 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.).²⁵ Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-13 and Table 3-14 provide mobile fossil fuel CH₄ and N₂O emission estimates in MMT CO₂ Eq.²⁶

Mobile combustion was responsible for a small portion of national CH₄ emissions (0.3 percent) but was the fourth largest source of U.S. N₂O emissions (4.0 percent). From 1990 to 2014, mobile source CH₄ emissions declined by 64 percent, to 2.0 MMT CO₂ Eq. (82 kt CH₄), due largely to control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH₄ emissions. Mobile source emissions of N₂O decreased by 60 percent, to 16.3 MMT CO₂ Eq. (55 kt N₂O). Earlier generation control technologies initially resulted in higher N₂O emissions, causing a 28 percent increase in N₂O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emission control technologies have reduced N₂O output, resulting in a 69 percent decrease in mobile source N₂O emissions from 1997 to 2014 (Figure 3-13). Overall, CH₄ and N₂O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

²⁴ Emissions of CH₄ 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.

²⁵ See the methodology sub-sections of the CO₂ from Fossil Fuel Combustion and CH₄ and N₂O from Mobile Combustion sections of this chapter. Note that N₂O and CH₄ emissions are reported using different categories than CO₂. CO₂ 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. CO₂ 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 CO₂ emissions are included in the Commercial end-use sector instead of the Transportation end-use sector). CH₄ and N₂O emissions are reported using the "Mobile Combustion" category, which includes non-transportation mobile sources. CH₄ and N₂O emissions 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, CO₂ emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

²⁶ See Annex 3.2 for a complete time series of emission estimates for 1990 through 2014.

Figure 3-13: Mobile Source CH₄ and N₂O Emissions (MMT CO₂ Eq.)

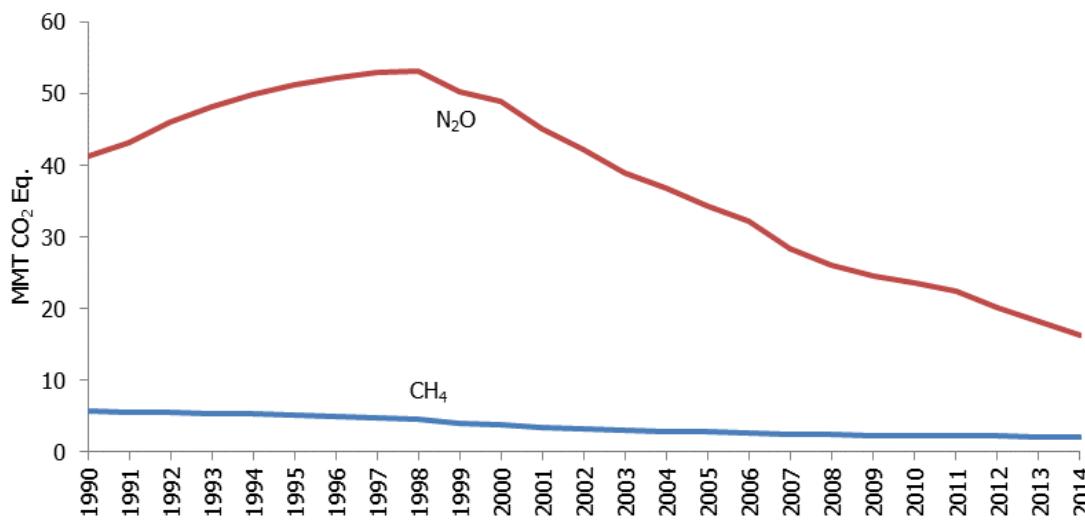


Table 3-13: CH₄ Emissions from Mobile Combustion (MMT CO₂ Eq.)

Fuel Type/Vehicle Type ^a	1990	2005	2010	2011	2012	2013	2014
Gasoline On-Road^b	5.2	2.2	1.7	1.6	1.5	1.5	1.4
Passenger Cars	3.2	1.2	1.2	1.2	1.1	1.0	1.0
Light-Duty Trucks	1.7	0.8	0.4	0.4	0.3	0.3	0.3
Medium- and Heavy-Duty							
Trucks and Buses	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road^b	+						
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty							
Trucks and Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road^c	+						
Non-Road^d	0.4	0.5	0.5	0.5	0.6	0.6	0.6
Ships and Boats	+	+	+	+	+	+	+
Rail ^e	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment ^f	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Construction/Mining							
Equipment ^g	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other ^h	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	5.6	2.7	2.3	2.2	2.2	2.1	2.0

+ 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 are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2015). These mileage 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 2015). TEDB data for 2014 has not been published yet, therefore 2013 data is used as a proxy.

^c In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the current inventory and apply to the 1990 through 2014 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

^d In 2015, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2014. This update resulted in small changes (less than 2 percent) to the 1999 through 2013 time series for NONROAD fuel consumption due to differences in the gasoline and diesel default fuel densities used within the model iterations.

^e Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 is not available yet, therefore 2013 data is used as a proxy.

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

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

^h “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.

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 2014 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.

Table 3-14: N₂O Emissions from Mobile Combustion (MMT CO₂ Eq.)

Fuel Type/Vehicle Type ^a	1990	2005	2010	2011	2012	2013	2014
Gasoline On-Road^b	37.5	29.9	19.2	18.0	15.7	13.8	12.1
Passenger Cars	24.1	15.9	12.9	12.3	10.7	9.3	7.9
Light-Duty Trucks	12.8	13.2	5.5	5.0	4.4	3.9	3.6
Medium- and Heavy-Duty							
Trucks and Buses	0.5	0.8	0.8	0.7	0.6	0.6	0.5
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road^b	0.2	0.3	0.4	0.4	0.4	0.4	0.4
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty							
Trucks and Buses	0.2	0.3	0.4	0.4	0.4	0.4	0.4
Alternative Fuel On-Road^c	+	+	+	0.1	0.1	0.1	0.1
Non-Road^d	3.5	4.1	4.0	4.0	3.9	3.9	3.8
Ships and Boats	0.6	0.6	0.8	0.8	0.7	0.7	0.5
Rail ^e	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Aircraft	1.7	1.8	1.4	1.4	1.3	1.4	1.4
Agricultural Equipment ^f	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Construction/Mining							
Equipment ^g	0.3	0.5	0.6	0.6	0.6	0.6	0.6
Other ^h	0.4	0.6	0.6	0.6	0.6	0.6	0.6
Total	41.2	34.4	23.6	22.4	20.0	18.2	16.3

^a Does not exceed 0.05 MMT CO₂ Eq.

^b See Annex 3.2 for definitions of on-road vehicle types.

^b Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2015). These mileage 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 2015). TEDB data for 2014 has not been published yet, therefore 2013 data is used as a proxy.

^c In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the current Inventory and apply to the 1990 through 2014 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

^d In 2015, EPA incorporated the NONROAD2008 model into MOVES2014. The current Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2014. This update resulted in small changes (less than two percent) to the 1999 through 2013 time series for NONROAD fuel consumption due to differences in the gasoline and diesel default fuel densities used within the model iterations.

^e Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 is not available yet, therefore 2013 data is used as a proxy.

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

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

^h "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.

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 2014 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.

CO₂ from Fossil Fuel Combustion

Methodology

The methodology used by the United States for estimating CO₂ emissions from fossil fuel combustion is conceptually similar to the approach recommended by the IPCC for countries that intend to develop detailed, sectoral-based emission estimates in line with a Tier 2 method in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).²⁷ The use of the most recently published calculation methodologies by the IPCC, as contained in the *2006 IPCC Guidelines*, is considered to improve the rigor and accuracy of this Inventory and is fully in line with IPCC Good Practice Guidance. 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, etc.), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil, etc.). 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 and published supplemental tables on petroleum product detail (EIA 2016). 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 2014) and Jacobs (2010).²⁸

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 data sets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.²⁹

²⁷ The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

²⁸ 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 41.2 MMT CO₂ Eq. in 2014.

²⁹ See IPCC Reference Approach for estimating CO₂ emissions from fossil fuel combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

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).³⁰

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 2013), Coffeyville (2014), U.S. Census Bureau (2011), EIA (2016), USGS (1991 through 2011), USGS (1994 through 2011), USGS (1995, 1998, 2000 through 2002), USGS (2007), USGS (2009), USGS (2010), USGS (2011), USGS (1991 through 2010a), USGS (1991 through 2010b), USGS (2012a) and USGS (2012b).³¹
3. *Adjust for conversion of fuels and exports of CO₂.* Fossil fuel consumption estimates are adjusted downward to exclude fuels created from other fossil fuels and exports of CO₂.³² Synthetic natural gas is created from industrial coal, and is currently included in EIA statistics for both coal and natural gas. Therefore, synthetic natural gas is subtracted from energy consumption statistics.³³ Since October 2000, the Dakota Gasification Plant has been exporting CO₂ to Canada by pipeline. Since this CO₂ is not emitted to the atmosphere in the United States, energy used to produce this CO₂ is subtracted from energy consumption statistics. To make these adjustments, additional data for ethanol were collected from EIA (2015), data for synthetic natural gas were collected from EIA (2014), and data for CO₂ exports were collected from the Eastman Gasification Services Company (2011), Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), EIA (2008) and DOE (2012).
4. *Adjust Sectoral Allocation of Distillate Fuel Oil and Motor Gasoline.* EPA had 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 was 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 2015), Benson (2002 through 2004), DOE (1993 through 2015), EIA (2007), EIA (1991 through 2015), EPA (2015c), and FHWA (1996 through 2015).³⁴

³⁰ 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.

³¹ 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.

³² Energy statistics from EIA (2015) are already adjusted downward to account for ethanol added to motor gasoline, and biogas in natural gas.

³³ These adjustments are explained in greater detail in Annex 2.1.

³⁴ The source of highway vehicle VMT and fuel consumption is FHWA's VM-1 table. 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 to 2010 Inventory and apply to the 2007 to 2014 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. 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 this emission Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

5. *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 the Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels section in this chapter. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption was provided by EIA (2016).
6. *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 international transport activities were calculated separately following the same procedures used for emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of C content).³⁵ 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 2015) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2016); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2014) for 1990 through 2001 and 2007 through 2014, and DHS (2008) for 2003 through 2006. Consumption of these fuels was subtracted from the corresponding fuels in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in the International Bunker Fuels section of this chapter.
7. *Determine the total C 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 CO₂. The C content coefficients used by the United States were obtained from EIA's *Emissions of Greenhouse Gases in the United States 2008* (EIA 2009a), and an EPA analysis of C content coefficients used in the GHGRP (EPA 2010). A discussion of the methodology used to develop the C content coefficients are presented in Annexes 2.1 and 2.2.
8. *Estimate CO₂ Emissions.* Total CO₂ emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the C 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).
9. *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 (2016) and USAF (1998).³⁶
 - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2014); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2013).
 - For non-road vehicles, activity data were obtained from AAR (2008 through 2015), APTA (2007 through 2015), APTA (2006), BEA (2016), Benson (2002 through 2004), DOE (1993 through 2015), DLA Energy (2015), DOC (1991 through 2015), DOT (1991 through 2015), EIA (2009a), EIA (2016), EIA (2013), EIA (1991 through 2015), EPA (2015c), and Gaffney (2007).

³⁵ See International Bunker Fuels section in this chapter for a more detailed discussion.

³⁶ For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO₂) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8.

- For jet fuel used by aircraft, CO₂ 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: 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 Greenhouse Gas Reporting Program (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 EPA's GHGRP 2010, 2011, 2012, 2013, and 2014 reporting years, facility-level fossil fuel combustion emissions reported through the 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.³⁷

This year's 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 UNFCCC, progress was made on certain fuel types for specific industries and has been included in the Common Reporting Format (CRF) tables that are submitted to the UNFCCC along with this report.³⁸ For the current exercise, the efforts in reconciling fuels focused on standard, common fuel types (e.g., natural gas, distillate fuel oil, etc.) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the 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. Additionally, this year's analysis expanded this effort through 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 2014 time series 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.

Additionally, to assist in the disaggregation of industrial fuel consumption, EIA will now synthesize energy consumption data using the same procedure as is used for the last historical (benchmark) year of the Annual Energy Outlook (AEO). This procedure reorganizes the most recent data from the Manufacturing Energy Consumption Survey (MECS) (conducted every four years) into the nominal data submission year using the same energy-economy integrated model used to produce the AEO projections, the National Energy Modeling System (NEMS). EIA believes this "nowcasting" technique provides an appropriate estimate of energy consumption for the CRF.

To address gaps in the time series, EIA performs a NEMS model projection, using the MECS baseline sub-sector energy consumption. The NEMS model accounts for changes in factors that influence industrial sector energy consumption, and has access to data which may be more recent than MECS, such as industrial sub-sector macro industrial output (i.e., shipments) and fuel prices. By evaluating the impact of these factors on industrial subsector

³⁷ 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-ccip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

³⁸ See <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>>.

energy consumption, NEMS can anticipate changes to the energy shares occurring post-MECS and can provide a way to appropriately disaggregate the energy-related emissions data into the CRF.

While the fuel consumption values for the various manufacturing sub-sectors are not directly surveyed for all years, they represent EIA's best estimate of historical consumption values for non-MECS years. Moreover, as an integral part of each AEO publication, this synthetic data series is likely to be maintained consistent with all available EIA and non-EIA data sources even as the underlying data sources evolve for both manufacturing and non-manufacturing industries alike.

Other sectors' fuel consumption (commercial, residential, transportation) will be benchmarked with the latest aggregate values from the Monthly Energy Review.³⁹ EIA will work with EPA to back cast these values to 1990.

Box 3-5: Carbon Intensity of U.S. Energy Consumption

Fossil fuels are the dominant source of energy in the United States, and CO₂ is the dominant greenhouse gas emitted as a product from their combustion. Energy-related CO₂ emissions are impacted by not only lower levels of energy consumption but also by lowering the C intensity of the energy sources employed (e.g., fuel switching from coal to natural gas). The amount of C emitted from the combustion of fossil fuels is dependent upon the C content of the fuel and the fraction of that C that is oxidized. Fossil fuels vary in their average C content, ranging from about 53 MMT CO₂ Eq./QBtu for natural gas to upwards of 95 MMT CO₂ Eq./QBtu for coal and petroleum coke.⁴⁰ In general, the C content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall C 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 3-15 provides a time series of the C intensity for each sector of the U.S. economy. The time series incorporates only the energy consumed from the direct combustion of fossil fuels in each sector. For the purposes of following reporting guidelines and maintaining the focus of this section, renewable energy and nuclear electricity and consumption are not included in the totals shown in Table 3-15 in order to focus attention on fossil fuel combustion as detailed in this chapter. For example, the C intensity for the residential sector does not include the energy from or emissions related to the consumption of electricity for lighting. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest C intensity, which is related to the large percentage of its energy derived from natural gas for heating. The C 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 C intensity of the transportation sector was closely related to the C content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO₂ Eq./EJ), which were the primary sources of energy. Lastly, the electricity generation sector had the highest C intensity due to its heavy reliance on coal for generating electricity.

Table 3-15: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO₂ Eq./QBtu)

Sector	1990	2005	2010	2011	2012	2013	2014
Residential ^a	57.4	56.6	55.8	55.7	55.5	55.3	55.4
Commercial ^a	59.1	57.5	56.8	56.6	56.1	55.8	55.8
Industrial ^a	64.3	64.3	62.9	62.4	62.0	61.8	61.5
Transportation ^a	71.1	71.4	71.5	71.5	71.5	71.4	71.4
Electricity Generation ^b	87.3	85.8	83.5	82.9	79.9	81.3	81.3
U.S. Territories ^c	73.0	73.4	73.1	73.1	72.4	72.1	71.6
All Sectors^c	73.0	73.5	72.4	72.0	70.9	70.9	70.7

^a Does not include electricity or renewable energy consumption.

³⁹ See <<http://www.eia.gov/totalenergy/data/monthly/>>.

⁴⁰ One exajoule (EJ) is equal to 10¹⁸ joules or 0.9478 QBtu.

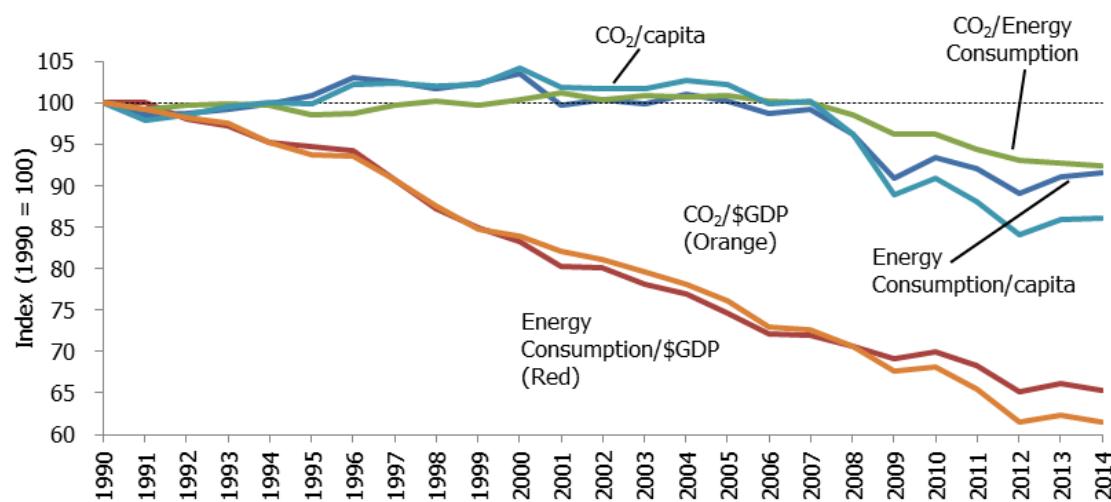
^b Does not include electricity produced using nuclear or renewable energy.

^c Does not include nuclear or renewable energy consumption.

Note: Excludes non-energy fuel use emissions and consumption.

Over the twenty-five-year period of 1990 through 2014, the C intensity of U.S. energy consumption has been fairly constant, as the proportion of fossil fuels used by the individual sectors has not changed significantly. Per capita energy consumption fluctuated little from 1990 to 2007, but in 2014 was approximately 8.5 percent below levels in 1990 (see Figure 3-14). To differentiate these estimates from those of Table 3-15, the C intensity trend shown in Figure 3-14 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 CO₂ emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2016).

Figure 3-14: U.S. Energy Consumption and Energy-Related CO₂ Emissions Per Capita and Per Dollar GDP



C intensity estimates were developed using nuclear and renewable energy data from EIA (2016), EPA (2010a), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty and Time-Series Consistency

For estimates of CO₂ from fossil fuel combustion, the amount of CO₂ 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 CO₂ 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 CO₂ emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990).

Although 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 problems in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO₂ emission estimate from energy-related fossil fuel combustion, the amount of fuel used in these non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO₂ 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. These factors all contribute to the uncertainty in the CO₂ 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 the International Bunker Fuels section of this chapter). 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 CO₂ 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 CO₂ 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 120 input variables were modeled for CO₂ from energy-related Fossil Fuel Combustion (including about 10 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.⁴¹ 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.⁴²

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).⁴³ For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-16. Fossil fuel combustion CO₂ emissions in 2014 were estimated to be between 5,102.4 and 5,457.4 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 5 percent above the 2014 emission estimate of 5,208.2 MMT CO₂ Eq.

⁴¹ 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.

⁴² 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.

⁴³ 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.

Table 3-16: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO₂ Eq. and Percent)

Fuel/Sector	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal^b	1,653.7	1,596.3	1,809.1	-3%	9%
Residential	NE	NE	NE	NE	NE
Commercial	4.5	4.3	5.2	-5%	15%
Industrial	75.3	71.8	87.2	-5%	16%
Transportation	NE	NE	NE	NE	NE
Electricity Generation	1,570.4	1,509.0	1,721.0	-4%	10%
U.S. Territories	3.4	3.0	4.0	-13%	19%
Natural Gas^b	1,426.6	1,411.4	1,492.7	-1%	5%
Residential	277.6	269.7	297.1	-3%	7%
Commercial	189.2	183.8	202.4	-3%	7%
Industrial	466.0	452.1	499.6	-3%	7%
Transportation	47.6	46.3	51.0	-3%	7%
Electricity Generation	443.2	430.4	465.6	-3%	5%
U.S. Territories	3.0	2.6	3.5	-12%	17%
Petroleum^b	2,127.5	1,997.0	2,251.9	-6%	6%
Residential	67.5	63.8	71.0	-5%	5%
Commercial	38.2	36.3	40.0	-5%	5%
Industrial	271.9	219.1	321.2	-19%	18%
Transportation	1,690.0	1,577.3	1,800.7	-7%	7%
Electric Utilities	25.3	24.1	27.3	-5%	8%
U.S. Territories	34.6	31.9	38.5	-8%	11%
Total (excluding Geothermal)^b	5,207.8	5,102.0	5,457.0	-2%	5%
Geothermal	0.4	NE	NE	NE	NE
Total (including Geothermal)^{b,c}	5,208.2	5,102.4	5,457.4	-2%	5%

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 CO₂ emissions from geothermal production.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for CO₂ from fossil fuel combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO₂ 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.

Recalculations Discussion

The Energy Information Administration (EIA 2016) updated energy consumption statistics across the time series relative to the previous Inventory. One such revision is the historical coal and petroleum product consumption in the industrial sector for the entire time series. In addition, EIA revised 2013 natural gas consumption in the

transportation sector and 2013 kerosene and Liquefied Petroleum Gas (LPG) consumption in the residential and commercial sectors.

Kerosene consumption increased in the residential sector by 9 percent in 2013 and decreased by 14 and 25 percent in the commercial and industrial sectors in 2013, respectively. Transportation sector distillate fuel consumption decreased by 0.4 percent across the entire time series.

In early 2015, EIA revised the heat content used to calculate the energy of distillate fuel oil consumption. Previously, a single constant factor (5.825 MMBtu/barrel) from EIA's Monthly Energy Review (MER) Table A1 was applied to the volumetric data. For the January 2015 release, this single constant factor in Table A1 was replaced with heat content factors for distillate fuel oil by sulfur content. Instead of using the factor(s) listed in Table A1, EIA began to use an annually variable quantity-weighted factor (5.774 MMBtu/barrel for 2013) that was added to Table A3. EIA notes that quantity-weighted averages of the sulfur-content categories of distillate fuel oil are calculated by using heat content values shown in Table A1, and that these values exclude renewable diesel fuel (including biodiesel) blended into distillate fuel oil.

Overall, these changes resulted in an average annual decrease of 1.1 MMT CO₂ Eq. (less than 0.1 percent) in CO₂ emissions from fossil fuel combustion for the period 1990 through 2013, relative to the previous report.

Planned Improvements

To reduce uncertainty of CO₂ from fossil fuel combustion estimates, efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. This improvement is not all-inclusive, and is part of an ongoing analysis and efforts to continually improve the CO₂ from fossil fuel combustion estimates. In addition, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from this source.

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 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 the GHGRP may also include industrial process emissions.⁴⁴ 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 CO₂ 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. Additional work will commence to ensure CO₂ 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 GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.⁴⁵

Another 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 is currently being investigated.

An additional potential improvement is to include CO₂ emissions from natural gas (LNG and CNG) use in medium- and heavy-duty trucks, light trucks and passenger cars. Currently data from the Transportation Energy Data book is

⁴⁴ See <<http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>>.

⁴⁵ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

used to allocate CO₂ emissions to vehicle categories. However, this data source only estimates natural gas use in buses. We are currently investigating the use of alternative data sources from the EIA that would allow some of the CO₂ from natural gas consumption to be allocated to these other vehicle categories.

In addition, we are investigating an approach to account for CO₂ emissions from the use of urea-based additives in catalytic converters for on-road vehicles between 2010 and 2014. The approach would utilize the MOVES model to estimate fuel use by diesel vehicles with urea-based catalysts. The *2006 IPCC Guidelines* estimates urea use between one and three percent of diesel fuel used.

CH₄ and N₂O from Stationary Combustion

Methodology

Methane and N₂O 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). Beginning with the current Inventory report, 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.

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 CH₄ and N₂O estimates, wood consumption data for the United States was obtained from EIA's Monthly Energy Review (EIA 2016). Fuel consumption data for coal, natural gas, and fuel oil for the United States were also obtained from EIA's Monthly Energy Review and unpublished supplemental tables on petroleum product detail (EIA 2016). 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 2014) and Jacobs (2010).⁴⁶ Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.⁴⁷ Construction and agricultural fuel use was obtained from EPA (2014). Estimates for wood biomass consumption for fuel combustion do not include wood wastes, liquors, municipal solid waste, tires, etc., that are reported as biomass by EIA. Tier 1 default emission factors for these three 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.

Electric Power Sector

The electric power sector now uses a Tier 2 emission estimation methodology as fuel consumption for the electricity generation sector by control-technology type was obtained from EPA's Acid Rain Program Dataset (EPA 2015a). This combustion technology- and fuel-use data was available by facility from 1996 to 2014. The Tier 2 emission factors used were taken from IPCC (2006), which in turn are based on emission factors published by EPA.

Since there was a difference between the EPA (2015a) and EIA (2016) total energy consumption estimates, the remaining energy consumption from EIA (2016) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2014.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2015a) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2016) and the ratio of combustion technology and fuel types from EPA (2015a). The consumption estimates from 1990 to 1995 were estimated by

⁴⁶ U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH₄ and N₂O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

⁴⁷ Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995. Emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors.

Lastly, there were significant differences between wood biomass consumption in the electric power sector between the EPA (2015a) and EIA (2016) datasets. The higher wood biomass consumption from EIA (2016) in the electric power sector was distributed to the residential, commercial, and industrial sectors according to their percent share of wood biomass energy consumption calculated from EIA (2016).

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

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 CH₄ and N₂O 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 CH₄ and N₂O stationary source inventory estimation models with the model for CO₂ 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 CO₂ 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 N₂O emission factors, based on the SAIC/EIA (2001) report.⁴⁸ For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).⁴⁹ However, the CH₄ 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 3-17. Stationary combustion CH₄ emissions in 2014 (*including* biomass) were estimated to be between 4.8 and 20.6 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 41 percent below to 155 percent above the 2014 emission estimate of 8.1 MMT CO₂ Eq.⁵⁰ Stationary combustion N₂O emissions in 2014 (*including* biomass) were estimated to be between 17.9 and 34.2 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 46 percent above the 2014 emissions estimate of 23.4 MMT CO₂ Eq.

⁴⁸ 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.

⁴⁹ 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.

⁵⁰ 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.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Stationary Combustion	CH ₄	8.1	4.8	20.6	-41%	+155%
Stationary Combustion	N ₂ O	23.4	17.9	34.2	-24%	+46%

^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 CH₄ and N₂O are greater than those associated with estimates of CO₂ from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH₄ and N₂O 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for stationary combustion was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH₄, N₂O, and the indirect greenhouse gases 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 N₂O emissions from stationary sources (excluding CO₂) across the entire time series were revised due to revised data from EIA (2016) and EPA (2015a) relative to the previous Inventory. The CH₄ emission estimates were also revised due to a corrected emission factor for Natural Gas Combined Cycle gas turbines that was corrected from 1 g/GJ to 4 g/GJ, per IPCC (2006). The historical data changes resulted in an average annual increase of less than 0.1 MMT CO₂ Eq. (less than 0.1 percent) in CH₄ emissions, and an average annual decrease of less than 0.1 MMT CO₂ Eq. (less than 0.1 percent) in N₂O emissions from stationary combustion for the period 1990 through 2013.

Planned Improvements

Several items are being evaluated to improve the CH₄ and N₂O emission estimates from stationary combustion and to reduce uncertainty. 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 since it was expected that the exclusion of biomass from the uncertainty 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 estimates.

Future improvements to the CH₄ and N₂O from Stationary Combustion category involve research into the availability of CH₄ and N₂O from stationary combustion data, and analyzing data reported under EPA's GHGRP. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for CH₄ and N₂O from Stationary Combustion category, particular attention will 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. 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.⁵¹

CH₄ and N₂O from Mobile Combustion

Methodology

Estimates of CH₄ and N₂O 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 are described in the subsections that follow. A complete discussion of the methodology used to estimate CH₄ and N₂O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH₄ and N₂O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors 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 by vehicle and fuel type.⁵²

Emission factors for gasoline and diesel on-road vehicles utilizing Tier 2 and Low Emission Vehicle (LEV) technologies were developed by ICF (2006b); all other gasoline and diesel on-road vehicle emissions factors were developed by ICF (2004). These factors were derived from EPA, California Air Resources Board (CARB) and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada tests were designed following the Federal Test Procedure (FTP), which 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 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 segment 2 were used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined 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 CO₂, CO, HC, NO_x, and PM from vehicles under various conditions, to approximate average driving characteristics.⁵³

Emission factors for AFVs were first developed by ICF (2006a) after examining Argonne National Laboratory's GREET 1.7–Transportation Fuel Cycle Model (ANL 2006) and Lipman and Delucchi (2002). These sources describe AFV emission factors in terms of ratios to conventional vehicle emission factors. Ratios of AFV to conventional vehicle emissions factors were then applied to estimated Tier 1 emissions factors from light-duty gasoline vehicles to estimate light-duty AFVs. Emissions factors for heavy-duty AFVs were developed in relation to gasoline heavy-duty vehicles. A complete discussion of the data source and methodology used to determine emission factors from AFVs is provided in Annex 3.2.

Annual VMT data for 1990 through 2014 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2015).⁵⁴ VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories

⁵¹ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

⁵² 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.

⁵³ Additional information regarding the model can be found online at <<http://www.epa.gov/OMS/m6.htm>>.

⁵⁴ The source of VMT is FHWA's VM-1 table. 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

using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2015) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2015). VMT for AFVs were estimated based on Browning (2015). The age distributions of the U.S. vehicle fleet were obtained from EPA (2015b, 2000), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2015b).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2007a, 2007b, 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).

Non-Road Vehicles

To estimate emissions from non-road vehicles, fuel consumption data were employed as a measure of activity, and multiplied by fuel-specific emission factors (in grams of N₂O and CH₄ per kilogram of fuel consumed).⁵⁵ Activity data were obtained from AAR (2008 through 2015), APTA (2007 through 2015), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), DHS (2008), DLA Energy (2015), DOC (1991 through 2015), DOE (1993 through 2015), DOT (1991 through 2015), EIA (2002, 2007, 2015a), EIA (2007 through 2015), EIA (1991 through 2015), EPA (2015b), Esser (2003 through 2004), FAA (2016), FHWA (1996 through 2015), Gaffney (2007), and Whorton (2006 through 2014). Emission factors for non-road modes were taken from IPCC (2006) and Browning (2009).

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 2014 estimates of CH₄ and N₂O 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 and (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 since 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 1.7 Uncertainty Analysis of Emission Estimates. However, a much higher level of uncertainty is associated with CH₄ and N₂O emission factors due to limited emission test data, and because, unlike CO₂ emissions, the emission pathways of CH₄ and N₂O are highly complex.

Mobile combustion CH₄ emissions from all mobile sources in 2014 were estimated to be between 1.8 and 2.4 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 12 percent below to 18 percent above the corresponding 2014 emission estimate of 2.0 MMT CO₂ Eq. Also at a 95 percent confidence level, mobile combustion N₂O emissions from mobile sources in 2014 were estimated to be between 15.7 and 20.7 MMT CO₂ Eq., indicating a range of 4 percent below to 27 percent above the corresponding 2014 emission estimate of 16.3 MMT CO₂ Eq.

2014 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 this Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

⁵⁵ The consumption of international bunker fuels is not included in these activity data, but is estimated separately under the International Bunker Fuels source category.

Table 3-18: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Mobile Sources (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate ^a (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH ₄	2.0	1.8	2.4	-12%	+18%
Mobile Sources	N ₂ O	16.3	15.7	20.7	-4%	+27%

^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 analysis. 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.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific Quality Assurance/Quality Control plan for mobile combustion was developed and implemented. This plan is based on the IPCC-recommended QA/QC Plan. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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 emissions 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

Decreases to CH₄ and N₂O emissions from mobile combustion are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES 2014a) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series. These changes are due to the updated MOVES age distributions for years 1999 through 2013 in this year's Inventory. These changes in the age distribution increased the percentage of vehicles and VMT for some vehicle types in newer model years that have better emissions control technology. For aircrafts, a weighted jet fuel heat content was applied to the jet fuel N₂O emissions calculation. The weighted factor accounts for the different heat contents of jet fuels used in commercial aviation, general aviation and the military. This resulted in a 0.4 percent increase in the heat content and a similar increase in N₂O emissions.

Estimates of alternative fuel vehicle mileage were also revised to reflect updates made to Energy Information Administration (EIA) data on alternative fuel use and vehicle counts. The energy economy ratios (EERs) in the alternative fuel vehicle analysis were also updated in this Inventory. EERs are the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles. These were taken from the Argonne National Laboratory's GREET model (ANL 2015). Most of the energy economy ratios were within 10 percent of their previous values. More significant changes occurred with Neighborhood Electric Vehicles (NEVs) (-26 percent), Electric Vehicles (EVs) (17 percent), Hydrogen Fuel Cell Vehicles (-15 percent), Neat Methanol Internal Combustion Engines (ICEs) (12 percent), Neat Ethanol ICEs (25 percent), LPG ICEs (11 percent) and LPG Bi-fuel (11 percent). Increases in EERs increase miles per gallon, estimated VMT, and emissions.

Overall, these changes resulted in an average annual decrease of 0.1 MMT CO₂ Eq. (4 percent) in CH₄ emissions and an average annual decrease of 1.4 MMT CO₂ Eq. (3 percent) in N₂O emissions from mobile combustion for the period 1990 through 2013, relative to the previous report.

Planned Improvements

While the data used for this report represent the most accurate information available, several areas have been identified that could potentially be improved in the near term given available resources.

- 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 is currently being investigated. Additionally, the feasibility of including data from a broader range of domestic and international sources for domestic bunker fuels, including data from studies such as the *Third IMO GHG Study 2014*, is being considered.
- Continue to examine the use of EPA's MOVES model in the development of the Inventory estimates, including use for uncertainty analysis. Although the Inventory uses some of the underlying data from MOVES, such as vehicle age distributions by model year, MOVES is not used directly in calculating mobile source emissions. The use of MOVES will be further explored.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (IPCC 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, liquefied petroleum gases (LPG), 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 non-energy products such as lubricants, waxes, and asphalt (IPCC 2006).

CO₂ 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 and across all uses, about 60 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 40 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 NEU products release CO₂ 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. In addition, there is some overlap between fossil fuels consumed for non-energy uses and the fossil-derived CO₂ emissions accounted for in the Industrial Processes and Product Use chapter, especially for fuels used as reducing agents. To avoid double-counting, the "raw" non-energy fuel consumption data reported by EIA are modified to account for these overlaps. There are also net exports of petrochemicals 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 3-19, fossil fuel emissions in 2014 from the non-energy uses of fossil fuels were 114.3 MMT CO₂ Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2014, the consumption of fuels for non-energy uses (after the adjustments described above) was 4,761.2 TBtu, an increase of 6.3 percent since 1990 (see Table 3-20). About 55.9 MMT (205.1 MMT CO₂ Eq.) of the C in these fuels was stored, while the remaining 31.2 MMT C (114.3 MMT CO₂ Eq.) was emitted.

Table 3-19: CO₂ Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO₂ Eq. and percent)

Year	1990	2005	2010	2011	2012	2013	2014
Potential Emissions	312.1	377.5	325.1	316.6	311.9	327.1	319.5
C Stored	194.0	238.6	211.0	208.1	206.2	205.4	205.1
Emissions as a % of Potential	38%	37%	35%	34%	34%	37%	36%
Emissions	118.1	138.9	114.1	108.5	105.6	121.7	114.3

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 (2013, 2015b) (see Annex 2.1). Consumption of natural gas, LPG, pentanes plus, naphthas, other oils, and special naphtha were adjusted to account for net exports of these products that are not reflected in the raw data from EIA. Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-20 and Table 3-21 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.^{56,57} Consumption values were also adjusted to subtract net exports of intermediary chemicals.

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, LPG, 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.
- For industrial coking coal and distillate fuel oil, storage factors were taken from IPCC (2006), which in turn draws from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), IPCC does not provide guidance on storage factors, and assumptions were made based on the potential fate of C in the respective NEU products.

Table 3-20: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2010	2011	2012	2013	2014
Industry	4,215.8	5,110.9	4,572.7	4,470.2	4,377.4	4,621.4	4,571.6
Industrial Coking Coal	+	80.4	64.8	60.8	132.5	119.6	23.0
Industrial Other Coal	8.2	11.9	10.3	10.3	10.3	10.3	10.3
Natural Gas to Chemical Plants	281.6	260.9	298.7	297.1	292.7	297.0	305.1

⁵⁶ 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.

⁵⁷ 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 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.

Asphalt & Road Oil	1,170.2	1,323.2	877.8	859.5	826.7	783.3	792.6
LPG	1,120.5	1,610.1	1,834.0	1,865.7	1,887.3	2,062.9	2,109.4
Lubricants	186.3	160.2	149.5	141.8	130.5	138.1	144.0
Pentanes Plus	117.6	95.5	75.3	26.4	40.3	45.4	43.5
Naphtha (<401 °F)	326.3	679.6	474.5	469.4	432.2	498.8	435.2
Other Oil (>401 °F)	662.1	499.5	433.2	368.2	267.4	209.1	236.2
Still Gas	36.7	67.7	147.8	163.6	160.6	166.7	164.6
Petroleum Coke	27.2	105.2	+	+	+	+	+
Special Naphtha	100.9	60.9	25.3	21.8	14.1	96.6	104.4
Distillate Fuel Oil	7.0	11.7	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	17.1	15.1	15.3	16.5	14.8
Miscellaneous Products	137.8	112.8	158.7	164.7	161.6	171.2	182.7
Transportation	176.0	151.3	141.2	133.9	123.2	130.4	136.0
Lubricants	176.0	151.3	141.2	133.9	123.2	130.4	136.0
U.S. Territories	86.7	121.9	56.4	56.7	58.1	57.4	53.6
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	86.0	117.3	55.4	55.7	57.1	56.4	52.6
Total	4,478.5	5,384.1	4,770.3	4,660.9	4,558.7	4,809.2	4,761.2

+ Does not exceed 0.05 TBtu

NA - Not Applicable

Note: Totals may not sum due to independent rounding.

Table 3-21: 2014 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use ^a (TBtu)	Carbon Content Coefficient (C/QBtu)	Carbon Potential Carbon (MMT C/QBtu)	Storage Factor	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO ₂ Eq.)
	Industry	4,571.6	NA	83.3	NA	55.6	27.7
Industrial Coking Coal	23.0	31.00	0.7	0.04	0.1	0.6	2.4
Industrial Other Coal	10.3	25.82	0.3	0.65	0.2	0.1	0.3
Natural Gas to Chemical Plants	305.1	14.46	4.4	0.65	2.9	1.5	5.6
Asphalt & Road Oil	792.6	20.55	16.3	1.00	16.2	0.1	0.3
LPG	2,109.4	17.06	36.0	0.65	23.6	12.4	45.6
Lubricants	144.0	20.20	2.9	0.09	0.3	2.6	9.7
Pentanes Plus	43.5	19.10	0.8	0.65	0.5	0.3	1.1
Naphtha (<401° F)	435.2	18.55	8.1	0.65	5.3	2.8	10.2
Other Oil (>401° F)	236.2	20.17	4.8	0.65	3.1	1.6	6.0
Still Gas	164.6	17.51	2.9	0.65	1.9	1.0	3.6
Petroleum Coke	+	27.85	+	0.04	+	+	+
Special Naphtha	104.4	19.74	2.1	0.65	1.3	0.7	2.6
Distillate Fuel Oil	5.8	20.17	0.1	0.04	0.1	0.1	0.2
Waxes	14.8	19.80	0.3	0.58	0.2	0.1	0.5
Miscellaneous Products	182.7	20.31	3.7	0.04	0.0	3.7	13.6
Transportation	136.0	NA	2.7	NA	0.3	2.5	9.1
Lubricants	136.0	20.20	2.7	0.09	0.3	2.5	9.1
U.S. Territories	53.6	NA	1.1	NA	0.1	1.0	3.5
Lubricants	1.0	20.20	+	0.09	+	+	0.1
Other Petroleum (Misc. Prod.)	52.6	20.00	1.1	0.04	0.1	0.9	3.5
Total	4,761.2		87.1		55.9	31.2	114.3

+ Does not exceed 0.05 TBtu

NA - Not Applicable

^aTo avoid double counting, net exports have been deducted.

Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-19). 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, 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 2015a), *Toxics Release Inventory, 1998* (2000b), *Biennial Reporting System* (EPA 2004, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015b), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011), and the Chemical Data Access Tool (EPA 2012); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013b, 2015b); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Bureau of the Census (1999, 2004, 2009); Bank of Canada (2012, 2013, 2014); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (1990-2015); Gosselin, Smith, and Hodge (1984); EPA's Municipal Solid Waste (MSW) Facts and Figures (EPA 2013a; 2014a); the Rubber Manufacturers' Association (RMA 2009, 2011, 2014); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001-2013); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003-2011, 2012, 2013, 2014a, 2014b, 2015); and the *Guide to the Business of Chemistry* (ACC 2015b). Specific data sources are listed in full detail in Annex 2.3.

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, LPG, pentanes plus, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the “other” category in Table 3-20 and Table 3-21), 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 3-22 (emissions) and Table 3-23 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2014 was estimated to be between 86.2 and 162.9 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 25 percent below to 42 percent above the 2014 emission estimate of 114.3 MMT CO₂ 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 3-22: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Non-Energy Uses of Fossil Fuels (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	75.1	49.6	125.3	-34%	67%
Asphalt	CO ₂	0.3	0.1	0.6	-57%	117%
Lubricants	CO ₂	18.9	15.5	21.9	-18%	16%
Waxes	CO ₂	0.5	0.3	0.7	-28%	63%
Other	CO ₂	19.6	14.1	21.7	-28%	11%
Total	CO₂	114.3	86.2	162.9	-25%	42%

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-23: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2014 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate ^a (%) (% Relative)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO ₂	65%	52%	72%	-20%	10%
Asphalt	CO ₂	99.6%	99.1%	99.8%	-0.5%	0.25%
Lubricants	CO ₂	9%	4%	17%	-57%	88%
Waxes	CO ₂	58%	49%	70%	-15%	22%
Other	CO ₂	4%	4%	24%	-3%	479%

^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).

In Table 3-23, 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific Quality Assurance/Quality Control plan for non-energy uses of fossil fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 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 for 2013 as well as their trends across the time series.

Petrochemical input data reported by EIA will continue to be investigated in an attempt to address an input/output discrepancy in the NEU model. Since 2001, the C accounted for in the feedstocks C balance outputs (i.e., storage plus emissions) exceeds C inputs. Prior to 2001, the C balance inputs exceed outputs. Starting in 2001 through 2009, outputs exceeded inputs. In 2010 and 2011, inputs exceeded outputs, and in 2012, outputs slightly exceeded inputs. A portion of this discrepancy has been reduced and two strategies have been developed to address the remaining portion (see Planned Improvements, below).

Recalculations Discussion

A number of updates to historical production values were included in the most recent Monthly Energy Review; these have been populated throughout this document.

Planned Improvements

There are several improvements planned for the future:

- Analyzing the fuel and feedstock data from EPA's GHGRP to better disaggregate CO₂ emissions in NEU model and CO₂ process emissions from petrochemical production.
- 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. 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, reconsider 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.
- Response to potential changes in NEU input data. In 2013 EIA initiated implementation of new data reporting definitions for Natural Gas Liquids (NGL) and Liquefied Petroleum Gases (LPG); the new definitions may affect the characterization of the input data that EIA provides for the NEU model and may therefore result in the need for changes to the NEU methodology. EIA also obtains and applies proprietary data for LPG inputs that are not directly applied as NEU input data because the data are proprietary. The potential use of the proprietary data (in an aggregated, non-proprietary form) as inputs to the NEU model will be investigated with EIA.
- 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 (miscellaneous products). A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses. For example, "miscellaneous

products” category 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 from petroleum and natural gas processing, and potentially also C black feedstock could be reported in this category. Recovered sulfur would not be reported in the NEU calculation or elsewhere in the Inventory.

- Updating the average C content of solvents was researched, since the entire time series depends on one year’s worth of solvent composition data. Unfortunately, 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 identified 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; 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.

Box 3-6: 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 Industrial Processes and Product Use (IPPU) sector.⁵⁸ 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 Emitted from Non-Energy Uses of Fossil Fuels source category (IPCC Source Category 1A).⁵⁹

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. 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 Section 3.2, Table 3-21). 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.⁶⁰ 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

⁵⁸ See Volume 3: Industrial Processes and Product Use, Chapter 5: Non-Energy Products from Fuels and Solvent Use of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006).

⁵⁹ 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.

⁶⁰ Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3: Methodology and Data for Estimating CO₂ Emissions from Fossil Fuel Combustion.

lubricants, waxes, and asphalt and road oil. Due to U.S. national circumstances, reporting these C emissions separately under IPPU would involve making artificial adjustments to both the C inputs and C outputs of the non-energy use C balance. These artificial adjustments would also result in the C emissions for lubricants, waxes, and asphalt and road oil being reported under IPPU, while the C storage for lubricants, waxes, and asphalt and road oil would be reported under Energy. 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.

3.3 Incineration of Waste (IPCC Source Category 1A1a)

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; 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, almost all incineration of MSW occurs 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 CO₂. According to IPCC guidelines, when the CO₂ emitted is of fossil origin, it is counted as a net anthropogenic emission of CO₂ 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 municipal solid wastes 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—plastics, synthetic rubber, synthetic fibers, and carbon black in scrap tires—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 municipal solid wastes 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 municipal solid waste. 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 29.6 million metric tons of MSW were incinerated in the United States in 2013 (EPA 2015). Data for the amount of MSW incinerated in 2014 were not available, so data for 2014 was assumed to be equal to data for 2013. CO₂ emissions from incineration of waste rose 18 percent since 1990, to an estimated 9.4 MMT CO₂ Eq. (9,421 kt) in 2014, as the volume of scrap tires and other fossil C-containing materials in waste increased (see Table 3-24 and Table 3-25). Waste incineration is also a source of CH₄ and N₂O emissions (De Soete 1993; IPCC 2006). Methane emissions from the incineration of waste were estimated to be less than 0.05 MMT CO₂ Eq. (less than 0.5 kt CH₄) in 2014, and have not changed significantly since 1990. Nitrous oxide emissions from the incineration of waste were estimated to be 0.3 MMT CO₂ Eq. (1 kt N₂O) in 2014, and have not changed significantly since 1990.

Table 3-24: CO₂, CH₄, and N₂O Emissions from the Incineration of Waste (MMT CO₂ Eq.)

Gas/Waste Product	1990	2005	2010	2011	2012	2013	2014 ^a
CO ₂	8.0	12.5	11.0	10.5	10.4	9.4	9.4
Plastics	5.6	6.9	6.0	5.8	5.7	4.9	4.9
Synthetic Rubber in Tires	0.3	1.6	1.5	1.4	1.3	1.2	1.2

Carbon Black in Tires	0.4	2.0	1.8	1.7	1.5	1.4	1.4
Synthetic Rubber in MSW	0.9	0.8	0.7	0.7	0.7	0.7	0.7
Synthetic Fibers	0.8	1.2	1.1	1.1	1.1	1.3	1.3
CH₄	+	+	+	+	+	+	+
N₂O	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Total	8.4	12.8	11.4	10.9	10.7	9.7	9.7

^a Set equal to 2013 value.

Table 3-25: CO₂, CH₄, and N₂O Emissions from the Incineration of Waste (kt)

Gas/Waste Product	1990	2005	2010	2011	2012	2013	2014 ^a
CO₂	7,972	12,454	11,026	10,550	10,362	9,421	9,421
Plastics	5,588	6,919	5,969	5,757	5,709	4,857	4,857
Synthetic Rubber in Tires	308	1,599	1,461	1,363	1,262	1,158	1,158
Carbon Black in Tires	385	1,958	1,783	1,663	1,537	1,412	1,412
Synthetic Rubber in MSW	854	765	701	712	705	729	729
Synthetic Fibers	838	1,212	1,112	1,056	1,149	1,265	1,265
CH₄	+	+	+	+	+	+	+
N₂O	2	1	1	1	1	1	1

^a Set equal to 2013 value.

Methodology

Emissions of CO₂ from the incineration of waste include CO₂ 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. These emissions were estimated by multiplying the amount of each material incinerated by the C content of the material and the fraction oxidized (98 percent). Plastics incinerated in municipal solid wastes 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 CO₂ 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 CO₂ 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 municipal solid waste (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), *Advancing Sustainable Materials Management: Facts and Figures 2013: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For 2014, the amount of MSW incinerated was assumed to be equal to that in 2013, due to the lack of available data. The proportion of total waste discarded that is incinerated was derived from Shin (2014). Data on total waste incinerated was not available for 2012 through 2014, so these values were assumed to equal the 2011 value. For synthetic rubber and carbon black in scrap tires, information was obtained from U.S. Scrap Tire Management Summary for 2005 through 2013 data (RMA 2014). Average C contents for the “Other” plastics category and synthetic rubber in municipal solid wastes 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 to date is based on the 2002 value. Carbon content for synthetic fibers was calculated from 1999 production statistics. Information about scrap tire composition was taken from the Rubber Manufacturers’ Association internet site (RMA 2012a).

The assumption that 98 percent of organic C is oxidized (which applies to all waste incineration categories for CO₂ emissions) was reported in EPA's life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006).

Incineration of waste, including MSW, also results in emissions of CH₄ and N₂O. These emissions were calculated as a function of the total estimated mass of waste incinerated and emission factors. As noted above, CH₄ and N₂O 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 2014, so these values were assumed to equal the 2011 *BioCycle* data set value.

Table 3-26 provides data on municipal solid waste discarded and percentage combusted for the total waste stream. The emission factors of N₂O and CH₄ emissions per quantity of municipal solid waste combusted are default emission factors for the default continuously-fed stoker unit MSW incineration technology type and were taken from IPCC (2006).

Table 3-26: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted (BioCycle data set)

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%
2010	271,592,991	22,714,122	8.0%
2011	273,116,704	20,756,870	7.6%
2012	273,116,704 ^a	20,756,870	7.6%
2013	273,116,704 ^a	20,756,870	7.6%
2014	273,116,704 ^a	20,756,870	7.6%

^a Assumed equal to 2011 value.

Source: van Haaren et al. (2010)

Uncertainty and Time-Series Consistency

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO₂ emissions and N₂O emissions from the incineration of waste (given the very low emissions for CH₄, 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 N₂O 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 3-27. Waste incineration CO₂ emissions in 2014 were estimated to be between 8.5 and 11.5 MMT CO₂ Eq. at a 95 percent confidence level.

This indicates a range of 10 percent below to 14 percent above the 2014 emission estimate of 9.4 MMT CO₂ Eq. Also at a 95 percent confidence level, waste incineration N₂O emissions in 2014 were estimated to be between 0.1 and 0.8 MMT CO₂ Eq. This indicates a range of 53 percent below to 163 percent above the 2014 emission estimate of 0.3 MMT CO₂ Eq.

Table 3-27: Approach 2 Quantitative Uncertainty Estimates for CO₂ and N₂O from the Incineration of Waste (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	9.4	8.5	11.5	-10%	+14%
Incineration of Waste	N ₂ O	0.3	0.1	0.8	-53%	+163%

^a Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific Quality Assurance/Quality Control plan was implemented for incineration of waste. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. 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. Actions were taken to streamline the activity data throughout the calculations on incineration of waste.

Recalculations Discussion

For the current Inventory, emission estimates for 2013 have been updated based on *Advancing Sustainable Materials Management: Facts and Figures 2013: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015).

The data which calculates the percent incineration was updated in the current Inventory. *Biocycle* has not released a new State of Garbage in America Report since 2010 (with 2008 data), which used to be a semi-annual publication which publishes the results of the nation-wide MSW survey. The results of the survey have been published in Shin 2014. This provided updated incineration data for 2011, so the generation and incineration data for 2012 through 2014 are assumed equivalent to the 2011 values. The data for 2009 and 2010 were based on interpolations between 2008 and 2011.

Planned Improvements

The availability of facility-level waste incineration data through EPA's Greenhouse Gas Reporting Program (GHGRP) will be examined to help better characterize waste incineration operations in the United States. This characterization could include future improvements as to the operations involved in waste incineration for energy, whether in the power generation sector or the industrial sector. Additional examinations will be necessary as, unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines,⁶¹ some facility-level waste incineration emissions reported under EPA's GHGRP may also include industrial process emissions. In line with UNFCCC reporting guidelines, emissions for waste incineration with energy recovery are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In

⁶¹ See <<http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>>.

examining data from EPA's GHGRP that would be useful to improve the emission estimates for the waste incineration 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 ensuring CO₂ emissions from the biomass component of waste are separated in the facility-level reported data, and on maintaining consistency with national waste generation and fate statistics currently used to estimate total, national U.S. greenhouse gas emissions. 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 GHGRP data is available for MSW combustors, which contains information on the CO₂, CH₄, and N₂O emissions from MSW combustion, plus the fraction of the emissions that are biogenic. To calculate biogenic versus total CO₂ emissions, a default biogenic fraction of 0.6 is used. The biogenic fraction will be calculated using the current input data and assumptions to verify the current MSW emission estimates.

If GHGRP data would not provide a more accurate estimate of the amount of solid waste combusted, new data sources for the total MSW generated will be explored given that the data previously published semi-annually in Biocycle (van Haaren et al. 2010) has ceased to be published, according to the authors. Equivalent data was derived from Shin (2014) for 2011. A new methodology would be developed based on the available data within the annual update of EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015). In developing the new methodology, appropriate assumptions would need to be made to ensure that the MSW figures included all waste. Additionally, the carbon content of the synthetic fiber will be updated based on each year's production mix.

Additional improvements will be conducted to improve the transparency in the current reporting of waste incineration. Currently, hazardous industrial waste incineration is included within the overall calculations for the Carbon Emitted from Non-Energy Uses of Fossil Fuels category. Waste incineration activities that do not include energy recovery will be examined. Synthetic fibers within scrap tires are not included in this analysis and will be explored for future inventories. The carbon content of fibers within scrap tires would be used to calculate the associated incineration emissions. Updated fiber content data from the Fiber Economics Bureau will also be explored.

3.4 Coal Mining (IPCC Source Category 1B1a)

Three types of coal mining–related activities release CH₄ 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 CH₄ emissions (see Table 3-29 and Table 3-30) due to the higher CH₄ content of coal in the deeper underground coal seams. In 2014, 345 underground coal mines and 613 surface mines were operating in the United States. In recent years the total number of active coal mines in the United States has declined. In 2014, the United States was the second largest coal producer in the world (906 MMT), after China (3,650 MMT) and followed by India (668 MMT) (IEA 2015).

Table 3-28: 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	334,398	789	691,448	1,398	1,025,846
2010	497	305,862	760	676,177	1,257	982,039
2011	508	313,529	788	684,807	1,296	998,337
2012	488	310,608	719	610,307	1,207	920,915
2013	395	309,546	637	581,270	1,032	890,815
2014	345	321,783	613	583,974	958	905,757

⁶² See <http://www.ipcc-nngip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

Underground mines liberate CH₄ 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 CH₄ 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 CH₄ before, during, or after mining. Some mines recover and use CH₄ generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH₄ as the overburden is removed and the coal is exposed to the atmosphere. CH₄ 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, CH₄ is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH₄ emissions in 2014 were estimated to be 2,703 kt (67.6 MMT CO₂ eq.), a decline of 30 percent since 1990 (see Table 3-29 and Table 3-30). Of this amount, underground mines accounted for approximately 73 percent, surface mines accounted for 14 percent, and post-mining emissions accounted for 13 percent.

Table 3-29: CH₄ Emissions from Coal Mining (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Underground (UG) Mining	74.2	42.0	61.6	50.2	47.3	46.2	49.1
Liberated	80.8	59.7	85.2	71.0	65.8	65.8	65.7
Recovered & Used	(6.6)	(17.7)	(23.6)	(20.8)	(18.5)	(19.6)	(16.6)
Surface Mining	10.8	11.9	11.5	11.6	10.3	9.7	9.6
Post-Mining (UG)	9.2	7.6	6.8	6.9	6.7	6.6	6.7
Post-Mining (Surface)	2.3	2.6	2.5	2.5	2.2	2.1	2.1
Total	96.5	64.1	82.3	71.2	66.5	64.6	67.6

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

Table 3-30: CH₄ Emissions from Coal Mining (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
UG Mining	2,968	1,682	2,463	2,008	1,891	1,849	1,964
Liberated	3,234	2,390	3,406	2,839	2,631	2,633	2,627
Recovered & Used	(266)	(708)	(943)	(831)	(740)	(784)	(662)
Surface Mining	430	475	461	465	410	388	386
Post-Mining (UG)	368	306	270	276	268	263	270
Post-Mining (Surface)	93	103	100	101	89	84	84
Total	3,860	2,565	3,293	2,849	2,658	2,584	2,703

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

Methodology

The methodology for estimating CH₄ emissions from coal mining consists of two steps:

- Estimate emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated on a mine-by-mine basis, then summed to determine total CH₄ liberated. The CH₄ recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH₄ 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 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 CH₄ Liberated and CH₄ Emitted from Underground Mines

Underground mines generate CH₄ from ventilation systems and from degasification systems. Some mines recover and use the generated CH₄, thereby reducing emissions to the atmosphere. Total CH₄ emitted from underground mines equals the CH₄ liberated from ventilation systems, plus the CH₄ liberated from degasification systems, minus the CH₄ recovered and used.

Step 1.1: Estimate CH₄ Liberated from Ventilation Systems

To estimate CH₄ liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP) (subpart FF, “Underground Coal Mines”), data provided by the U.S. Mine Safety and Health Administration (MSHA), and occasionally data collected from other sources on a site-specific level (e.g., state data). Since 2011, the nation’s “gaggiest” underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH₄ per year (about 14,700 MT CO₂ eq.)—have been required to report to EPA’s GHGRP (EPA 2015).⁶³ Mines that report to the GHGRP must report quarterly measurements of CH₄ emissions from ventilation systems to EPA; they have the option of recording 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 CH₄ concentrations.⁶⁴

Since 2013, ventilation emission estimates have been calculated based on both GHGRP data submitted by underground mines that recorded their own measurements, and on quarterly measurement data obtained directly from MSHA for the remaining mines (not MSHA data reported by the mines to the GHGRP).⁶⁵ The quarterly measurements are used to determine the average daily emissions rate for the reporting year quarter.

Step 1.2: Estimate CH₄ Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH₄ before, during, or after mining. This CH₄ can then be collected for use or vented to the atmosphere. Twenty-five mines used degasification systems in 2014, and the CH₄ removed through these systems was reported to EPA’s GHGRP (EPA 2015). Based on the weekly measurements reported to EPA’s GHGRP, degasification data summaries for each mine were added together to estimate the CH₄ liberated from degasification systems. Sixteen of the 25 mines with degasification systems had operational CH₄ recovery and use projects (see step 1.3 below), and GHGRP reports show the remaining nine mines vented CH₄ from degasification systems to the atmosphere.⁶⁶

Degassification volumes for the life of any pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.⁶⁷ EPA’s GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under subpart FF. Most pre-mining wells drilled from the surface are considered coalbed methane wells and are reported under another subpart of the program (subpart W, “Petroleum and Natural Gas Systems”). As a result, for the 10 mines with degassification systems that include pre-mining wells, GHGRP information was supplemented with historical data from state gas well production databases (GSA 2016, WVGES 2015), as well as with mine-specific information regarding the dates on which the pre-mining wells are mined through (JWR 2010, El Paso 2009).

Degassification information reported to EPA’s GHGRP by underground coal mines was the primary source of data used to develop estimates of CH₄ liberated from degassification systems. Data reported to EPA’s GHGRP were used to estimate CH₄ liberated from degassification systems at 20 of the 25 mines that employed degassification systems in 2014. For the other five mines (all with pre-mining wells from which CH₄ was recovered), GHGRP data—along with supplemental information from state gas production databases (GSA 2016, WVGES 2015)—were used to

⁶³ Underground coal mines report to EPA under Subpart FF of the GHGRP. In 2014, 128 underground coal mines reported to the program.

⁶⁴ MSHA records coal mine CH₄ readings with concentrations of greater than 50 ppm (parts per million) CH₄. Readings below this threshold are considered non-detectable.

⁶⁵ EPA has determined that certain mines are having difficulty interpreting the MSHA data so that they report them correctly to the GHGRP. EPA is working with these mines to correct their GHGRP reports, and in the meantime is relying on data obtained directly from MSHA for purposes of the national inventory.

⁶⁶ Several of the mines venting CH₄ from degassification systems use a small portion the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH₄ use is not considered to be a formal recovery and use project.

⁶⁷ A well is “mined through” when coal mining development or the working face intersects the borehole or well.

estimate CH₄ liberated from degasification systems. For one mine, due to a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the CH₄ liberated was based on both the reported GHGRP data (for the vented portion of CH₄ recovered) and an estimate from historical mine-provided CH₄ recovery and use rates based on gas sales records (JWR 2010, El Paso 2009).

Step 1.3: Estimate CH₄ Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Sixteen mines had CH₄ recovery and use projects in place in 2014. Fourteen of these mines sold the recovered CH₄ to a pipeline, including one that also used CH₄ to fuel a thermal coal dryer. In addition, one mine used recovered CH₄ for electrical power generation, and one used recovered CH₄ to heat mine ventilation air.

Ten of the 16 mines deployed degasification systems in 2014; for those mines, estimates of CH₄ recovered from the systems were exclusively based on GHGRP data. Based on weekly measurements, the GHGRP degasification destruction data summaries for each mine were added together to estimate the CH₄ recovered and used from degasification systems.

All 10 mines with degasification systems used pre-mining wells as part of those systems, but only four of them intersected pre-mining wells in 2014. GHGRP and supplemental data were used to estimate CH₄ recovered and used at two of these four mines; supplemental data alone (GSA 2016) were used for the other two mines, which reported to EPA's GHGRP as a single entity. Supplemental information was used for these four mines because estimating CH₄ 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. The supplemental data came from state gas production databases, as well as mine-specific information on the timing of mined-through pre-mining wells.

GHGRP information was not used to estimate CH₄ recovered and used at two mines. At one of these mines, a portion (16 percent) of reported CH₄ vented was applied to an ongoing mine air heating project. Because of a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the 2014 CH₄ recovered and used at the other mine was based on an estimate from historical mine-provided CH₄ recovery and use rates (including emissions avoided from pre-mining wells).

In 2014, one mine destroyed a portion of its CH₄ emissions from ventilation systems using thermal oxidation technology. The amount of CH₄ recovered and destroyed by the project was determined through publicly-available emission reduction project information (CAR 2015).

Step 2: Estimate CH₄ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were 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 2015) was 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 (see King 1994, Saghafi 2013). For post-mining activities, basin-specific coal production was multiplied by basin-specific gas 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 daily emissions rate for the quarter. 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). GHGRP data were used for a significant number of the mines that reported their own measurements to the program beginning in 2013; however, the equipment uncertainty is applied to both GHGRP and MSHA data.

Estimates of CH₄ recovered by degasification systems are relatively certain for utilized CH₄ because of the availability of GHGRP data and gas sales information. Many of the 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 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 utilized CH₄ 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 subsource. 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 3-31. Coal mining CH₄ emissions in 2014 were estimated to be between 59.9 and 77.4 MMT CO₂ eq. at a 95 percent confidence level. This indicates a range of 11.9 percent below to 15.3 percent above the 2014 emission estimate of 67.6 MMT CO₂ eq.

Table 3-31: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Coal Mining (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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 mining	CH ₄	67.6	59.9	77.4	-11.9%	+15.3%

^a Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

Note: Emissions values are presented in CO₂ equivalent mass units using IPCC AR4 GWP values.

Methodological recalculations were applied to the entire time-series to ensure consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the methodology section.

Recalculations Discussion

For the current Inventory, no recalculations were performed on prior inventory years.

Planned Improvements

Future improvements to the coal mining category will include continued analysis and integration into the national inventory of the degasification quantities and ventilation emissions data reported by underground coal mines to EPA's GHGRP. A higher reliance on EPA's GHGRP will provide greater consistency and accuracy in future inventories. MSHA data will serve as a quality assurance tool for validating GHGRP data. Reconciliation of the GHGRP and Inventory data sets is still in progress. In implementing improvements and integrating data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied on (IPCC 2011).

3.5 Abandoned Underground Coal Mines (IPCC 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 CH₄ 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 CH₄ that may find its way to surface structures through overburden fractures. As work stops within the mines, CH₄ liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH₄ 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 CH₄ 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;
- CH₄ flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH₄ emissions ranged from 7.2 to 10.8 MMT CO₂ Eq. from 1990 through 2014, 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 CO₂ Eq.) due to the large number of gassy mine⁶⁸ 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. There were seven gassy mine closures in 2014. In 2014, gross abandoned mine emissions decreased slightly to 8.7 MMT CO₂ Eq. (see Table 3-32 and Table 3-33). Gross emissions are reduced by CH₄ recovered and used at 37 mines, resulting in net emissions in 2014 of 6.3 MMT CO₂ Eq.

Table 3-32: CH₄ Emissions from Abandoned Coal Mines (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Abandoned Underground Mines	7.2	8.4	9.7	9.3	8.9	8.8	8.7
Recovered & Used	+	1.8	3.2	2.9	2.7	2.6	2.4
Total	7.2	6.6	6.6	6.4	6.2	6.2	6.3

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

⁶⁸ A mine is considered a “gassy” mine if it emits more than 100 thousand cubic feet of CH₄ per day (100 mcfd).

Table 3-33: CH₄ Emissions from Abandoned Coal Mines (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Abandoned Underground Mines	288	334	389	373	358	353	350
Recovered & Used	+	70	126	116	109	104	97
Total	288	264	263	257	249	249	253

+ Does not exceed 0.5 kt

Note: Totals may not sum due to independent rounding.

Methodology

Estimating CH₄ 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 CH₄ 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 CH₄ emission rate before abandonment reflects the gas content of the coal, 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 which 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 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 CH₄ 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 CH₄ 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 CH₄ 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 (mmcf/d)
- q_i = Initial gas flow rate at time zero (t₀), mmcf/d
- b = The hyperbolic exponent, dimensionless
- D_i = Initial decline rate, 1/yr
- t = Elapsed time from t₀ (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 CH₄ 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. There was not enough data to establish basin-specific equations as was done with the vented, non-flooding mines (EPA 2004).

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd
 q_i = Initial gas flow rate at time zero (to), mmcfd
 D = Decline rate, 1/yr
 t = Elapsed time from to (years)

Seals have an inhibiting effect on the rate of flow of CH₄ 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 $100 \times (1 - [\text{initial emissions from sealed mine} / \text{emission rate at abandonment prior to sealing}])$. 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 (mcf) account for 98 percent of all CH₄ emissions. This same relationship is assumed for abandoned mines. It was determined that the 500 abandoned mines closed after 1972 produced emissions greater than 100 mcf when active. Further, the status of 291 of the 500 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 CH₄ 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 3-34: Number of Gassy Abandoned Mines Present in U.S. Basins in 2014, grouped by Class according to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	37	25	51	113	137	250
Illinois	32	3	14	49	27	76
Northern Appl.	43	22	16	81	36	117
Warrior Basin	0	0	16	16	0	16
Western Basins	27	3	2	32	9	41
Total	139	53	99	291	209	500

Inputs to the decline equation require the average emission rate and the date of abandonment. Generally this data is 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 CH₄ emissions from coal mining came from seventeen counties in seven states. In addition, 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 United States, representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH₄ emissions rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH₄ ventilation emission rates greater than 100 mcf 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 2015). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect ventilation emissions only for pre-1990 closures. CH₄ degasification amounts were added to the quantity of CH₄ vented to determine the total CH₄ liberation rate for all mines that closed between 1992 and 2014. Since the sample of gassy mines 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 2014, emission totals were downwardly adjusted to reflect abandoned mine CH₄ emissions avoided from those mines. The Inventory totals were not adjusted for abandoned mine reductions from 1990 through 1992 because no data was reported for abandoned coal mining CH₄ recovery projects during that time.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis was conducted to estimate the uncertainty surrounding the estimates of emissions from abandoned underground coal mines. The uncertainty analysis described below 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) CH₄ 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 3-35. Annual abandoned coal mine CH₄ emissions in 2014 were estimated to be between 5.2 and 7.9 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 18 percent below to 24 percent above the 2014 emission estimate of 6.3 MMT CO₂ 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 after 1972. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH₄ liberation rates exist.

Table 3-35: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Abandoned Underground Coal Mines (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	6.3	5.2	7.9	-18%	+24%

^a Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.6 Petroleum Systems (IPCC Source Category 1B2a)

Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil production, transportation, and refining operations. During these activities, CH₄ is released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Fugitive and vented CO₂ emissions from petroleum systems are primarily associated with crude oil production and refining

operations but are negligible in transportation operations. Total CH₄ emissions from petroleum systems in 2014 were 68.1 MMT CO₂ Eq. (2,726 kt).

Production Field Operations. Production field operations account for approximately 99 percent of total CH₄ emissions from petroleum systems. Vented CH₄ from field operations account for approximately 92 percent of the net emissions from the production sector, fugitive emissions are approximately 5 percent, uncombusted CH₄ emissions (i.e., unburned fuel) account for approximately 4 percent, and process upset emissions are 0.1 percent. The most dominant sources of emissions from production field operations are pneumatic controllers, oil tanks, chemical injection pumps, offshore oil platforms, hydraulic fractured oil well completions, gas engines, and oil wellheads. These sources alone emit over 95 percent of the production field operations emissions. The remaining 5 percent of the emissions are distributed among around 20 additional activities.

Since 1990, CH₄ emissions from production field operations have increased by nearly 80 percent. Total methane emissions (from all segments) have increased by around 5 percent from 2013 levels.

Vented CO₂ associated with production field operations account for approximately 99 percent of the total CO₂ emissions from production field operations, while fugitive and process upsets together account for approximately 1 percent of the emissions. The most dominant sources of CO₂ emissions are oil tanks, pneumatic controllers, chemical injection pumps, and offshore oil platforms. These five sources together account for slightly over 97 percent of the non-combustion CO₂ emissions from production field operations, while the remaining 3 percent of the emissions is distributed among around 20 additional activities. Note that CO₂ from associated gas flaring is accounted in natural gas systems production emissions. Total CO₂ emissions from flaring for both natural gas and oil were 20.8 MMT CO₂ Eq. in 2014.

Crude Oil Transportation. Crude oil transportation activities account for approximately 0.3 percent of total CH₄ emissions from the oil industry. Venting from tanks, truck loading, rail loading, and marine vessel loading operations account for 84 percent of CH₄ emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for approximately 12 percent of CH₄ emissions from crude oil transportation. The remaining 4 percent is distributed between two additional sources within the vented emissions category (i.e., pump station maintenance and pipeline pigging), and fugitive emissions from pump stations.

Since 1990, CH₄ emissions from transportation have increased by almost 24 percent. However, because emissions from crude oil transportation account for such a small percentage of the total emissions from the petroleum industry, this has had little impact on the overall emissions. Methane emissions from transportation have increased by approximately 13 percent from 2013 levels.

Crude Oil Refining. Crude oil refining processes and systems account for approximately 1 percent of total CH₄ emissions from the oil industry because most of the CH₄ in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is an insignificant amount of CH₄ in all refined products. Within refineries, combustion emissions account for slightly over 50 percent of the CH₄ emissions, while vented and fugitive emissions account for approximately 31 and 19 percent, respectively. Flare emissions are the primary combustion emissions contributor, accounting for approximately 79 percent of combustion CH₄ emissions. Refinery system blowdowns for maintenance and process vents are the primary venting contributors (96 percent). Most of the fugitive CH₄ emissions from refineries are from equipment leaks and storage tanks (89 percent).

Methane emissions from refining of crude oil have decreased by approximately 1.4 percent since 1990; however, similar to the transportation subcategory, this decrease has had little effect on the overall emissions of CH₄. Since 1990, CH₄ emissions from crude oil refining have fluctuated between 23 and 28 kt.

Flare emissions from crude oil refining accounts for slightly more than 94 percent of the total CO₂ emissions in petroleum systems. Refinery CO₂ emissions decreased by slightly more than 7 percent from 1990 to 2014.

Table 3-36: CH₄ Emissions from Petroleum Systems (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Production Field Operations							
(Potential)	38.0	48.9	54.8	56.6	58.7	64.7	68.1
Pneumatic controller venting ^a	19.0	30.2	33.2	33.7	33.3	37.7	39.2
Tank venting	6.3	4.7	5.3	5.5	7.0	8.2	9.9
Combustion & process upsets	2.9	2.3	2.5	2.5	2.7	2.9	3.1
Misc. venting & fugitives	8.4	10.5	12.5	13.5	14.3	14.3	14.5

Wellhead fugitives	1.5	1.2	1.4	1.4	1.5	1.5	1.5
Production Voluntary Reductions	(0.0)	(0.9)	(1.5)	(1.1)	(1.1)	(0.8)	(0.8)
Production Field Operations							
(Net)	38.0	48.0	53.3	55.4	57.5	63.9	67.4
Crude Oil Transportation	0.2	0.1	0.1	0.1	0.2	0.2	0.2
Refining	0.6	0.7	0.6	0.7	0.7	0.6	0.6
Total	38.7	48.8	54.1	56.3	58.4	64.7	68.1

^a Values presented in this table for pneumatic controllers are net emissions. The revised methodology for the 2016 (current) Inventory incorporates GHGRP subpart W activity and emissions data, and is detailed in the Recalculations Discussion section.

Notes: Totals may not sum due to independent rounding. Parentheses indicate emissions reductions.

Table 3-37: CH₄ Emissions from Petroleum Systems (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Production Field Operations							
(Potential)	1,519	1,957	2,193	2,263	2,347	2,586	2,725
Pneumatic controller venting ^a	761	1,209	1,328	1,346	1,332	1,509	1,567
Tank venting	250	188	210	220	278	330	396
Combustion & process upsets	115	91	98	101	108	114	122
Misc. venting & fugitives	334	421	502	540	570	573	578
Wellhead fugitives	59	48	54	56	59	60	62
Production Voluntary Reductions	(0)	(36)	(60)	(45)	(45)	(31)	(31)
Production Field Operations							
(Net)	1,519	1,921	2,133	2,218	2,302	2,556	2,694
Crude Oil Transportation	7	5	5	5	6	7	8
Refining	24	27	26	28	27	26	23
Total	1,550	1,953	2,163	2,251	2,335	2,588	2,726

^a Values presented in this table for pneumatic controllers are net emissions. The revised methodology for the 2016 (current) Inventory incorporates GHGRP subpart W activity and emissions data, and is detailed in the Recalculations Discussion section.

Notes: Totals may not sum due to independent rounding. Parentheses indicate emissions reductions.

Table 3-38: CO₂ Emissions from Petroleum Systems (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Production Field Operations							
0.4	0.3	0.4	0.4	0.5	0.6	0.6	0.6
Pneumatic controller venting	+	0.1	0.1	0.1	0.1	0.1	0.1
Tank venting	0.3	0.2	0.3	0.3	0.4	0.4	0.5
Misc. venting & fugitives	+	+	+	+	+	+	+
Wellhead fugitives	+	+	+	+	+	+	+
Process upsets	+	+	+	+	+	+	+
Crude Refining	3.2	3.6	3.8	3.8	3.4	3.1	2.9
Total	3.6	3.9	4.2	4.2	3.9	3.7	3.6

+ Does not exceed 0.05 MMT CO₂ Eq.

Notes: Totals may not sum due to independent rounding.

Table 3-39: CO₂ Emissions from Petroleum Systems (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Production Field Operations							
391	338	379	395	473	550	640	
Pneumatic controller venting	42	67	74	75	74	84	87
Tank venting	328	246	276	288	365	432	519
Misc. venting & fugitives	17	21	26	28	30	30	30
Wellhead fugitives	3	3	3	3	3	3	3
Process upsets	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Crude Refining	3,162	3,589	3,775	3,797	3,404	3,143	2,927
Total	3,553	3,927	4,154	4,192	3,876	3,693	3,567

Note: Totals may not sum due to independent rounding.

Methodology

The estimates of CH₄ emissions from petroleum systems are largely based on GRI/EPA 1996, EPA 1999, and EPA's GHGRP data (EPA 2015a). Petroleum Systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil production field operations, crude oil transportation activities, and refining operations. Annex 3.5 provides detail on the emission estimates for these activities. The estimates of CH₄ emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are negligible.

Emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by the corresponding activity data (e.g., equipment count or frequency of activity).

References for emission factors include DrillingInfo (2015), "Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA" (EPA/GRI 1996a-d), "Estimates of Methane Emissions from the U.S. Oil Industry" (EPA 1999), consensus of industry peer review panels, BOEMRE and BOEM reports (BOEMRE 2004, BOEM 2011), analysis of BOEMRE data (EPA 2005, BOEMRE 2004), and the GHGRP (2010 through 2014).

Emission factors from EPA 1999 are used for all activities except those related to pneumatic controllers, chemical injection pumps, hydraulic fractured oil well completions, offshore oil production, field storage tanks, and refineries. The emission factors for pneumatic controllers venting and chemical injection pumps were developed using EPA's GHGRP data for reporting year 2014. Emission factors for hydraulically fractured (HF) oil well completions (controlled and uncontrolled) were developed using data analyzed for the 2015 NSPS OOOOa proposal (EPA 2015b). For oil storage tanks, the emissions factor was calculated as the total emissions per barrel of crude charge from E&P Tank data weighted by the distribution of produced crude oil gravities from the HPDI production database (EPA 1999, HPDI 2011). For offshore oil production, two emission factors were calculated using data collected for all federal offshore platforms (EPA 2015c, BOEM 2014), one for oil platforms in shallow water, and one for oil platforms in deep water. For all sources, emission factors are held constant for the period 1990 through 2014.

References for activity data include DrillingInfo (2015), the Energy Information Administration annual and monthly reports (EIA 1990 through 2015), (EIA 1995 through 2015a, 2015b), "Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA" (EPA/GRI 1996a-d), "Estimates of Methane Emissions from the U.S. Oil Industry" (EPA 1999), consensus of industry peer review panels, BOEMRE and BOEM reports (BOEMRE 2004, BOEM 2011), analysis of BOEMRE data (EPA 2005, BOEMRE 2004), the Oil & Gas Journal (OGJ 2015), the Interstate Oil and Gas Compact Commission (IOGCC 2012), the United States Army Corps of Engineers, (1995 through 2015), and the GHGRP (2010 through 2014).

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. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA 1996, and/or GHGRP data. In other cases, the activity data were held constant from 1990 through 2014 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. For offshore production, the number of platforms in shallow water and the number of platforms in deep water are used as activity data and are taken from Bureau of Ocean Energy Management (BOEM) (formerly Bureau of Ocean Energy Management, Regulation, and Enforcement [BOEMRE]) datasets (BOEM 2011a,b,c).

For petroleum refining activities, 2010 to 2014 emissions were directly obtained from EPA's GHGRP. All refineries have been required to report CH₄ and CO₂ emissions for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2014 emissions. The national emission totals for each activity were divided by refinery feed rates for those four Inventory years to develop average activity-specific emission factors, which were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for each year (EPA 2015d).

The Inventory estimate for Petroleum Systems takes into account Natural Gas STAR reductions. Voluntary reductions included in the Petroleum Systems calculations were those reported to Natural Gas STAR for the following activities: artificial lift - gas lift; artificial lift - use compression; artificial lift - use pumping unit; consolidate crude oil production and water storage tanks; lower heater-treater temperature; re-inject gas for enhanced oil recovery; re-inject gas into crude; and route casinghead gas to vapor recovery unit or compressor.

The methodology for estimating CO₂ emissions from petroleum systems includes calculation of vented, fugitive, and process upset emissions sources from 29 activities for crude oil production field operations and three activities from petroleum refining. Generally, emissions are estimated for each activity by multiplying CO₂ emission factors by their corresponding activity data. The emission factors for CO₂ are generally estimated by multiplying the CH₄ emission factors by a conversion factor, which is the ratio of CO₂ content and CH₄ content in produced associated gas. One exception to this methodology is the set of emission factors for crude oil storage tanks, which are obtained from E&P Tank simulation runs, and the emission factors for offshore oil production (shallow and deep water), which were derived using data from BOEM (EPA 2015c, BOEM 2014). Other exceptions to this methodology are the three petroleum refining activities (i.e., flares, asphalt blowing, and process vents); the CO₂ emissions data for 2010 to 2014 were directly obtained from the GHGRP. The 2010 to 2013 CO₂ emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CO₂ emission factors (i.e., sum of activity emissions/sum of refinery feed) which were then applied to the annual refinery feed to estimate CO₂ emissions for 1990 to 2009.

Uncertainty and Time-Series Consistency

The most recent uncertainty analysis for the petroleum systems emission estimates in the Inventory was conducted for the 1990 to 2009 Inventory that was released in 2011. Since the analysis was last conducted, several of the methods used in the Inventory have changed, and industry practices and equipment have evolved. In addition, new studies and other data sources such as those discussed in the sections below offer improvement to understanding and quantifying the uncertainty of some emission source estimates. EPA is planning an update to the uncertainty analysis conducted for the 2011 Inventory to reflect the new information. It is difficult to project whether updated uncertainty bounds around CH₄ emission estimates would be wider, tighter, or about the same as the current uncertainty bounds that were developed for the Inventory published in 2011 (i.e., minus 24 percent and plus 149 percent). Details on EPA's planned uncertainty analysis are described in the Planned Improvements section.

EPA conducted a quantitative uncertainty analysis for the 2011 Inventory to determine the level of uncertainty surrounding estimates of emissions from petroleum systems using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique). The @RISK software model was used to quantify the uncertainty associated with the emission estimates using the 7 highest-emitting sources ("top 7 sources") for the year 2010. The @RISK 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 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 analysis conducted for the 2011 Inventory has not yet been updated for the 1990 through 2014 Inventory years; instead, EPA has applied the uncertainty percentage ranges calculated previously to 2014 emission estimates. The majority of sources in the current Inventory were calculated using the same emission factors and activity data for which PDFs were developed in the 1990 through 2009 uncertainty analysis. However, as discussed in the Methodology and Recalculations Discussion sections, EPA has revised the methodology and data for many emission sources. Given these revisions, the 2009 uncertainty ranges applied may not reflect the uncertainty associated with the recently revised emission factors and activity data sources.

The results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall for the year 2014, based on the previously conducted uncertainty assessment using the recommended IPCC methodology. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-40. Petroleum systems CH₄ emissions in 2014 were estimated to be between 51.8 and 101.5 MMT CO₂ Eq., while CO₂ emissions were estimated to be between 2.7 and 5.4 MMT CO₂ Eq. at a 95 percent confidence level, based on previously calculated uncertainty. This indicates a range of 24 percent below to 149 percent above the 2014 emission estimates of 68.1 and 3.6 MMT CO₂ Eq. for CH₄ and CO₂, respectively.

Table 3-40: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Petroleum Systems (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	68.1	51.8	101.5	-24%	149%
Petroleum Systems	CO ₂	3.6	2.7	5.4	-24%	149%

^a Range of 2014 relative uncertainty predicted by Monte Carlo Stochastic Simulation, based on 1995 base year activity factors, for a 95 percent confidence interval.

^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 compared the quantitative uncertainty estimate for CH₄ emissions from petroleum systems to those reported in the recently published study by Lyon et al., (2015) (see “Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates” [EPA 2016a]).⁶⁹ Lyon et al., (2015) used the Monte Carlo simulation technique to examine uncertainty bounds for the estimates developed by that study for the Barnett Shale. The uncertainty range in the study differ from those of EPA. However, it is difficult to extrapolate an uncertainty range from this study that can be applied to the Inventory estimate because the coverage of the Lyon et al. (2015) study is limited to the 25-county Barnett Shale area, the reported estimate encompasses natural gas in addition to petroleum system emissions, and the two estimates use different methodologies and data sources.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification Discussion

The petroleum system 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. In addition, EPA receives feedback through the annual expert and public review period. Feedback received is noted in the Recalculations and Planned Improvement sections.

Recalculations Discussion

The EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories’ formal public notice periods, GHGRP data, and new studies. The EPA carefully evaluated relevant information available, and made revisions to the production segment methodology for the 2016 (current) Inventory including revised equipment activity data, revised pneumatic controller activity and emissions data, and included a separate estimate for hydraulically fractured oil well completions, which previously were not estimated as a distinct subcategory of oil well completions.

In February 2016, the EPA released a draft memorandum, “Revisions under Consideration for Natural Gas and Petroleum Production Emissions,” that discussed the changes under consideration and requested stakeholder

⁶⁹ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

feedback on those changes. Please see
<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

The combined impact of revisions to 2013 petroleum production segment emissions, compared to the 1990-2013 Inventory, is an increase in CH₄ emissions from 24.2 to 63.9 MMT CO₂ Eq. (40 MMT CO₂ Eq., or 164 percent).

The recalculations resulted in an average increase in emission estimates across the 1990 to 2013 time series, compared to the previous (2015) Inventory, of 21 MMT CO₂ Eq., or an 85 percent. The largest increases in the estimate occurred in later years of the time series.

Production

This section references the final 2016 (current) Inventory memorandum, “Revisions to Natural Gas and Petroleum Production Emissions” (EPA 2016b).⁷⁰ “Revisions to Natural Gas and Petroleum Production Emissions” contains further details and documentation of recalculations (EPA 2016b).

Updated activity factors for fugitives, pumps and controllers

Using newly available GHGRP activity data, the EPA developed activity factors (i.e., counts per oil well) for separators, headers, heater-treaters, pneumatic pumps, and pneumatic controllers. EPA reviewed this new data source and the previous data, assessed stakeholder feedback, and determined that the previous data source represents activities from the time period in which the data were collected (early 1990s) and the new GHGRP data source represents activities from recent years. The EPA applied the updated activity factors to calculate emissions from these sources for year 2011-on in the 2016 (current) Inventory petroleum production segment, while retaining the previous activity factors for 1990 through 1992. For years 1993 through 2010, the EPA calculated equipment counts by linearly interpolating between the data points of calculated national equipment counts in 1992 (based on GRI/EPA) and calculated national equipment counts in 2011 (based on GHGRP). This reflects an assumed gradual transition from the counts observed in the 1996 study and the counts observed in the recent GHGRP data.

For the year 2013, the CH₄ emissions increase due to use of revised activity factors for major equipment and pneumatic pumps is approximately 4.2 MMT CO₂ Eq.

Table 3-41: CH₄ Emissions from Sources with Updates to use GHGRP Data (MMT CO₂ Eq.)

Type	Source	1990	2005	2010	2013	2014
Venting	Chemical Injection Pumps	1.2	3.4	4.3	4.7	4.8
	<i>Previous-Chemical</i>					
<i>Venting</i>	<i>Injection Pumps</i>	<i>1.4</i>	<i>1.2</i>	<i>1.3</i>	<i>1.4</i>	
Fugitive	Oil Wellheads	1.5	1.2	1.4	1.5	1.5
	<i>Previous-Oil Wellheads</i>	<i>1.5</i>	<i>1.2</i>	<i>1.3</i>	<i>1.5</i>	
Fugitive	Separators	0.3	0.6	0.8	0.8	0.9
	<i>Previous-Separators</i>	<i>0.3</i>	<i>0.2</i>	<i>0.2</i>	<i>0.3</i>	
Fugitive	Heater/Treaters	0.3	0.3	0.4	0.4	0.4
	<i>Previous-Heater/Treaters</i>	<i>0.3</i>	<i>0.2</i>	<i>0.3</i>	<i>0.3</i>	
Fugitive	Headers	0.1	0.2	0.2	0.2	0.2
	<i>Previous-Headers</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	
Fugitive	Compressors	0.1	+	+	0.1	0.1
	<i>Previous-Compressors</i>	<i>0.1</i>	<i>+</i>	<i>+</i>	<i>+</i>	

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Values in *italics* are from the previous Inventory.

Using the GHGRP data, the EPA has also developed technology-specific activity data and emission factors for pneumatic controllers. Data reported under EPA’s GHGRP allow for development of emission factors specific to bleed type (continuous high bleed, continuous low bleed, and intermittent bleed) and separation of activity data into these categories. EPA used this separation of pneumatic controller counts by bleed types and emission factors developed from reported GHGRP data. Comparing the updated 2013 estimate to the previous Inventory 2013

⁷⁰ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

estimate, the impact of using bleed type-specific emission factors and activity data developed from GHGRP data is an increase of approximately 26 MMT CO₂ Eq. Over the 1990 through 2013 time series, the average increase due to the recalculation is 16 MMT CO₂ Eq.

Table 3-42: CH₄ Emissions from Pneumatic Controllers (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
All	19.0	30.2	33.2	37.7	39.2
High bleed	17.8	17.5	12.6	5.5	4.7
Low bleed	1.2	1.8	2.0	1.4	1.2
Intermittent bleed	+	10.9	18.6	30.9	33.3
<i>Previous-All</i>	<i>12.2</i>	<i>10.1</i>	<i>10.8</i>	<i>11.9</i>	<i>NA</i>
<i>Previous-High bleed</i>	<i>9.5</i>	<i>7.8</i>	<i>8.4</i>	<i>9.2</i>	<i>NA</i>
<i>Previous-Low bleed</i>	<i>2.8</i>	<i>2.3</i>	<i>2.4</i>	<i>2.7</i>	<i>NA</i>

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

The EPA's approach to revising the Inventory methodology by incorporating technology-specific GHGRP data for pneumatic controllers resulted in net emissions being directly calculated for these sources in each time series year. This methodology revision obviates the need to apply Gas STAR reductions data for pneumatic controllers as had been done in previous Inventories. EPA removed the pneumatic controller Gas STAR reductions from its calculations.

Oil Well Completions

The Inventory previously did not distinguish between oil well completions and workovers with hydraulic fracturing (HF) and oil well completions and workovers without hydraulic fracturing. The Inventory emission factors for all oil well completions and workovers were developed using an assumption that all oil well workovers and completions are flared. In the current Inventory, an estimate for the subcategories of oil well completions with hydraulic fracturing with and without controls was included. This estimate was developed using an uncontrolled emission factor developed as part of the analysis supporting the OOOOa NSPS proposal (7.5 tons CH₄/completion)⁷¹, and a controlled emission factor that assumes 95 percent control efficiency (0.4 tons CH₄/completion). For the OOOOa proposal analysis, EPA extracted gas production data from oil well records in DrillingInfo, and developed average daily gas production rates (over the first month of production) for wells that were determined to have been completed with hydraulic fracturing in 2012. The average value for these wells was 255.47 Mcf/day. This was then multiplied by a 3 day completion duration, and a methane content value of 47 percent to develop the uncontrolled factor. Total annual national HF oil well completion data were developed from DrillingInfo data (DrillingInfo 2015). The Inventory uses the NSPS OOOOa proposal information for the percentage of oil well completions that are controlled due to state regulations, 7 percent and applies that value beginning in 2008. It is assumed in the inventory estimate that prior to 2008, all oil well completions with HF are uncontrolled. The inventory continues to use one estimate for workover emissions for completions of all types (i.e. both hydraulically fractured and non-hydraulically fractured). This recalculation results in a 3 MMT CO₂ Eq. increase from the previous 2013 estimate for completions and workovers, and an average increase of 1 MMT CO₂ Eq. over the 1990 through 2013 time series.

Table 3-43: CH₄ Emissions from Oil Well Completions and Workovers (C&W) (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
HF Completions	0.6	0.9	1.7	3.0	3.0
NonHF Completions	+	+	+	+	+
Workovers (HF and nonHF)	+	+	+	+	+
Total C&W	0.6	0.9	1.7	3.0	3.0

⁷¹ The value presented in the NSPS proposal, 9.72 short tons was the average emissions calculated for the subset of HF oil well completions with GOR >300 scf/bbl. The inventory averaged emissions from the same base data set, without the GOR <300 scf/bbl exclusion, so that for the inventory, the emission factor can be applied to all HF oil well completions in the U.S., including those with lower GOR.

Previous Total C&W +  +  +  + **NA**

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Values in *italics* are from the previous Inventory.

Planned Improvements

In response to the public review draft and earlier released memorandum outlining potential revisions to the production segment, EPA received feedback from stakeholders that will be further considered to refine future Inventories.

In the production segment, some commenters suggested that the approach taken overestimates equipment counts in the production segment, while others suggested that the approach was appropriate. The EPA will further consider how activity factors developed from GHGRP data may over- or under-represent equipment counts for non-GHGRP facilities (those not meeting the emissions reporting threshold). Preliminary assessment by EPA of this issue by disaggregating GHGRP reporter data by number of wells reported indicated that reporters with fewer wells had higher equipment counts per well than average. EPA will continue to explore other methods to assess whether the non-GHGRP population may have different average equipment counts than the reporting population and how this may be reflected in the Inventory. EPA will continue to assess GHGRP data for additional updates to the inventory. While comments received supported the update to include hydraulically fractured oil well completions as a distinct subcategory category, commenters differed on the recommended data for the update (DI Desktop approach versus GHGRP data). EPA will review the first year of reported GHGRP data on hydraulically fractured oil well completions and workovers and will consider how it may be used to update the inventory. Additionally, EPA received comments suggesting that EPA use associated gas venting and flaring data from GHGRP and apply it to the population of associated gas wells in the Inventory, to address the concern that casinghead gas emissions occur at a wider set of associated gas wells, not only at stripper wells. EPA will investigate the appropriateness of using associated gas venting and flaring data from the GHGRP to replace or supplement current estimates of casinghead gas venting from stripper wells in the 2017 Inventory.

In response to the public review memoranda, EPA also received feedback from stakeholders on aspects of emission sources that were not significantly revised in the 2016 (current) Inventory. Stakeholders noted that data generated by Allen et al. in recent studies of pneumatic controller emissions in the production segment might be used to develop a separate emission factor for malfunctioning devices (in addition to the bleed type-specific factors developed from GHGRP data and used in the 2016 [current] Inventory). EPA will evaluate available data studies on this emission source.

EPA will continue to consider stakeholder feedback on the methodology used to develop counts of active oil wells across the time series.

EPA will continue to consider methods to refine the time series. For many sources with, the time series calculations rely on linear interpolation between 1990's data points and 2011 data points.

Abandoned wells are not currently accounted for in the Inventory. EPA is seeking appropriate emission factors and national activity data available to calculate these emissions. Commenters supported including this source category, noted the currently data is limited, and suggested reviewing data that will become available in the future.

Uncertainty

As discussed in the Recalculations Discussion section above, EPA made several revisions to the methodology and data for the 2016 (current) Inventory. As noted in the Uncertainty section above, EPA has not yet updated its uncertainty analysis to reflect this new information. It is difficult to project whether the uncertainty bounds around CH₄ emission estimates would be wider, tighter, or about the same as the current uncertainty bounds that were developed for the Inventory published in 2011 (i.e., minus 24 percent and plus 149 percent) given these revisions.

To update its uncertainty analysis, EPA will conduct a formal quantitative uncertainty analysis similar to that conducted for the 2011 Inventory using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique) using new data and taking into account stakeholder input received. For more information, please see "Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty

Estimates” (EPA 2016a).⁷² As in the 2011 Inventory analysis, EPA will first identify a select number of top-emitting emission sources for each source category. Refer to “Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates” for more information on planned improvements regarding uncertainty (EPA 2016a).

Box 3-7: 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. This CO₂ is produced from both naturally-occurring CO₂ reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the Inventory, emissions from naturally-produced CO₂ are estimated based on the specific application.

In the Inventory, CO₂ 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. The naturally-occurring CO₂ used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO₂ emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO₂ is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Production sections of the Inventory report, respectively.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO₂. 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 CO₂ 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 CO₂ emissions estimates for geologic storage.

In the United States, facilities that produce CO₂ for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO₂, exporters of CO₂, facilities that conduct geologic sequestration of CO₂, and facilities that inject CO₂ underground (including facilities conducting EOR), are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities conducting geologic sequestration of CO₂ are required to develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and to report the amount of CO₂ sequestered using a mass balance approach.

Available GHGRP data relevant for this inventory estimate consists of national-level annual quantities of CO₂ captured and extracted for EOR applications for 2010 to 2014. In the current Inventory, the previous estimates for 2010 to 2013 were replaced with GHGRP data for 2010 to 2013, and estimates for 2014 were directly taken from the reported GHGRP data for 2014. For the year 2013, this update has resulted in an increase of approximately 28 percent over the previous estimate. Using the GHGRP data has resulted in an average annual increase of approximately 11 MMT CO₂ Eq., or by approximately 25 percent, over the time series 2010 through 2013.

EPA will continue to evaluate the availability of additional GHGRP data and other opportunities for improving the emission estimates.

These estimates indicate that the amount of CO₂ captured and extracted from industrial and natural sites for EOR applications in 2014 is 59.3 MMT CO₂ Eq. (59,318 kt) (see Table 3-44 and Table 3-45). Site-specific monitoring and reporting data for CO₂ injection sites (i.e., EOR operations) were not readily available, therefore, these estimates assume all CO₂ is emitted.

Table 3-44: Potential Emissions from CO₂ Capture and Extraction for EOR Operations (MMT CO₂ Eq.)

Stage	1990	2005	2010	2011	2012	2013	2014
Capture Facilities	4.8	6.5	9.9	9.9	9.3	12.2	13.1
Extraction Facilities	20.8	28.3	44.8	48.4	48.9	47.0	46.2
Total	25.6	34.7	54.7	58.2	58.1	59.2	59.3

⁷² See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

Table 3-45: Potential Emissions from CO₂ Capture and Extraction for EOR Operations (kt)

Stage	1990	2005	2010	2011	2012	2013	2014
Capture Facilities	4,832	6,475	9,900	9,877	9,267	12,205	13,093
Extraction Facilities	20,811	28,267	44,759	48,370	48,869	46,984	46,225
Total	25,643	34,742	54,659	58,247	58,136	59,189	59,318

3.7 Natural Gas Systems (IPCC 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. Overall, natural gas systems emitted 176.1 MMT CO₂ Eq. (7,045 kt) of CH₄ in 2014, a 15 percent decrease compared to 1990 emissions, and a slight (i.e., less than 1 percent) increase compared to 2013 emissions (see Table 3-46, Table 3-47, and Table 3-48) and 42.4 MMT CO₂ Eq. (42,351 kt) of non-combustion CO₂ in 2014, a 12 percent increase compared to 1990 emissions.

The 1990 to 2014 trend is not consistent across segments. Overall, the 1990 to 2014 decrease in CH₄ emissions is due primarily to the decrease in emissions from in the transmission/storage and distribution segments. Over the same time period, the production and processing segments saw increased methane emissions, of 31 and 13 percent, respectively. Natural gas systems also emitted 42.4 MMT CO₂ Eq. (42,351 kt) of non-combustion CO₂ in 2014, a 12 percent increase compared to 1990 emissions, and a 10 percent increase from 2013 emissions (see Table 3-49 and Table 3-50). Both the 1990 to 2014 and the 2013 to 2014 increases in CO₂ are due primarily to flaring; the volume of gas flared increased 93 percent from 1990 and 12 percent from 2013.

CH₄ and non-combustion CO₂ 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, bleed and discharge emissions from pneumatic controllers, and fugitive 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. Below is a characterization of the four major stages of the natural gas system. Each of the stages is described and the different factors affecting CH₄ and non-combustion CO₂ emissions are discussed.

Production (including gathering and boosting). In the production stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and well-site gas treatment facilities such as dehydrators and separators. Gathering and boosting emission sources are not reported under a unique segment, but are included within the production sector. The gathering and boosting segment of natural gas systems comprises 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). Emissions from production (including gathering and boosting) account for 62 percent of CH₄ emissions and 44 percent of non-combustion CO₂ emissions from natural gas systems in 2014. Emissions from gathering stations, pneumatic controllers, kimray pumps, liquids unloading, condensate tanks, gathering pipeline leaks, and offshore platforms account for the majority of CH₄ emissions in 2014. Flaring emissions account for the majority of the non-combustion CO₂ emissions. CH₄ emissions from production increased by 31 percent from 1990 to 2014, due primarily to increases in emissions from gathering and boosting stations (due to an increase in the number of stations), increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers), and condensate tanks (due to an increase in condensate produced). CO₂ emissions from production increased 88 percent from 1990 to 2014 due primarily to increases in flaring.

Processing. In this stage, 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. Fugitive CH₄ emissions from compressors, including compressor seals, are the primary emission source from this stage. The majority of non-combustion CO₂ emissions come from acid gas removal (AGR) units, which are designed to remove CO₂ from natural gas.

Processing plants account for 14 percent of CH₄ emissions and 56 percent of non-combustion CO₂ emissions from natural gas systems. CH₄ emissions from processing increased by 13 percent from 1990 to 2014 as emissions from compressors increased along with the quantity of gas produced. CO₂ emissions from processing decreased by 15 percent from 1990 to 2014, as a result of a decrease in acid gas removal emissions.

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, which contain large reciprocating and turbine compressors, are used to move the gas throughout the U.S. transmission system. Fugitive CH₄ emissions from these compressor stations, and venting from pneumatic controllers account for the majority of the emissions from this stage. Uncombusted engine exhaust and pipeline venting are also sources of CH₄ 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). Compressors and dehydrators are the primary contributors to emissions from storage. CH₄ emissions from the transmission and storage sector account for approximately 18 percent of emissions from natural gas systems, while CO₂ emissions from transmission and storage account for less than 1 percent of the non-combustion CO₂ emissions from natural gas systems. CH₄ emissions from this source decreased by 45 percent from 1990 to 2014 due to reduced compressor station emissions (including emissions from compressors and fugitives). CO₂ emissions from transmission and storage have decreased by 37 percent from 1990 to 2014, also due to reduced compressor station emissions.

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 1,264,340 miles of distribution mains in 2014, an increase of over 320,000 miles since 1990 (PHMSA 2015). Distribution system emissions, which account for 6 percent of CH₄ emissions from natural gas systems and less than 1 percent of non-combustion CO₂ emissions, result mainly from fugitive emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH₄ and CO₂ emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH₄ emissions in 2014 were 74 percent lower than 1990 levels (changed from 43.5 MMT CO₂ Eq. to 11.1 MMT CO₂ Eq.), while distribution CO₂ emissions in 2014 were 72 percent lower than 1990 levels (CO₂ emission from this segment are less than 0.1 MMT CO₂ Eq. across the time series).

Total CH₄ emissions for the four major stages of natural gas systems are shown in MMT CO₂ Eq. (Table 3-46) and kt (Table 3-47). Table 3-48 provides additional information on how the estimates in Table 3-46 were calculated. Table 3-48 shows the calculated CH₄ release (i.e., potential emissions before any controls are applied) from each stage, and the amount of CH₄ that is estimated to have been flared, captured, or otherwise controlled, and therefore not emitted to the atmosphere. Subtracting the value for CH₄ that is controlled, from the value for calculated potential release of CH₄, results in the total emissions values. More disaggregated information on potential emissions and emissions is available in Annex 3.6. See Methodology for Estimating CH₄ and CO₂ Emissions from Natural Gas Systems.

Table 3-46: CH₄ Emissions from Natural Gas Systems (MMT CO₂ Eq.)^a

Stage	1990	2005	2010	2011	2012	2013	2014
Field Production	83.4	108.1	108.3	108.8	111.1	110.7	109.0
Processing	21.3	16.4	17.9	21.3	22.3	22.6	24.0
Transmission and Storage	58.6	30.7	27.5	28.8	27.9	30.8	32.1
Distribution	43.5	22.1	12.5	11.2	11.4	11.5	11.1
Total	206.8	177.3	166.2	170.1	172.6	175.6	176.1

^a These values represent CH₄ emitted to the atmosphere. CH₄ that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-47: CH₄ Emissions from Natural Gas Systems (kt)^a

Stage	1990	2005	2010	2011	2012	2013	2014
Field Production	3,335	4,326	4,330	4,352	4,442	4,429	4,359
Processing	852	655	717	851	890	904	960
Transmission and Storage	2,343	1,230	1,100	1,152	1,116	1,232	1,282
Distribution	1,741	884	500	449	457	458	444
Total	8,270	7,093	6,647	6,803	6,906	7,023	7,045

^a These values represent CH₄ emitted to the atmosphere. CH₄ that is captured, flared, or otherwise controlled (and not emitted to the atmosphere) has been calculated and removed from emission totals.

Note: Totals may not sum due to independent rounding.

Table 3-48: Calculated Potential CH₄ and Captured/Combusted CH₄ from Natural Gas Systems (MMT CO₂ Eq.)

	1990	2005	2010	2011	2012	2013	2014
Calculated Potential^a	206.9	202.7	196.3	196.5	199.6	202.3	203.8
Field Production	83.5	115.7	120.5	121.3	123.6	124.2	123.3
Processing	21.3	20.6	23.6	25.2	26.2	26.5	27.9
Transmission and Storage	58.6	43.1	38.3	37.3	37.3	39.1	40.4
Distribution	43.5	23.3	13.9	12.7	12.5	12.5	12.1
Captured/Combusted^b	0.1	25.4	30.1	26.4	27.0	26.7	27.7
Field Production	0.1	7.6	12.2	12.5	12.5	13.5	14.4
Processing	+	4.2	5.7	3.9	3.9	3.9	4.0
Transmission and Storage	+	12.4	10.8	8.5	9.4	8.3	8.4
Distribution	+	1.2	1.4	1.5	1.1	1.0	1.0
Net Emissions	206.8	177.3	166.2	170.1	172.6	175.6	176.1
Field Production	83.4	108.1	108.3	108.8	111.1	110.7	109.0
Processing	21.3	16.4	17.9	21.3	22.3	22.6	24.0
Transmission and Storage	58.6	30.7	27.5	28.8	27.9	30.8	32.1
Distribution	43.5	22.1	12.5	11.2	11.4	11.5	11.1

+ Does not exceed 0.1 MMT CO₂ Eq.

^a In this context, “potential” means the total emissions calculated before voluntary reductions and regulatory controls are applied.

^b In 2014, over half of the capture and combustion accounted here is in the production segment, while 14 percent is from processing, 30 percent from transmission and storage, and 4 percent from distribution. For additional information, please see Annex 3.6.

Note: Totals may not sum due to independent rounding.

Table 3-49: Non-combustion CO₂ Emissions from Natural Gas Systems (MMT CO₂ Eq.)

Stage	1990	2005	2010	2011	2012	2013	2014
Field Production	9.9	8.3	11.0	14.1	13.7	16.6	18.6
Processing	27.8	21.7	21.3	21.5	21.5	21.8	23.7
Transmission and Storage	0.1	+	+	+	+	+	+
Distribution	0.1	+	+	+	+	+	+
Total	37.7	30.1	32.4	35.7	35.2	38.5	42.4

+ Does not exceed 0.1 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 3-50: Non-combustion CO₂ Emissions from Natural Gas Systems (kt)

Stage	1990	2005	2010	2011	2012	2013	2014
Field Production	9,857	8,260	11,041	14,146	13,684	16,649	18,585
Processing	27,763	21,746	21,346	21,466	21,469	21,756	23,713

Transmission and Storage	62	43	37	36	35	37	39
Distribution	50	27	16	15	14	14	14
Total	37,732	30,076	32,439	35,662	35,203	38,457	42,351

Note: Totals may not sum due to independent rounding.

Methodology

The methodology for natural gas emissions estimates presented in this Inventory involves the calculation of CH₄ and CO₂ emissions for over 100 emissions sources, 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 some sources, the approach uses what are considered “potential methane factors,” and reduction data to calculate net emissions; for other sources, the approach uses technology-specific emission factors or emission factors that vary over time to take into account changes to technologies and practices, and these calculate net emissions directly.

The approach of calculating potential CH₄ and then applying reductions data to calculate net emissions was used to ensure a time series that reflects real emission trends. As noted below, key data on emissions from many sources are from 1996 GRI/EPA report containing data collected in 1992. Since the time of this study, practices and technologies have changed. While this study still represents best available data for some emission sources, using these emission factors alone to represent actual emissions without adjusting for emissions controls would, in many cases, overestimate emissions. As updated emission factors reflecting changing practices are not available for some sources, the 1992 emission factors continue to be used for some sources for all years of the Inventory, but they are considered to be potential emissions factors, representing what emissions would be if practices and technologies had not changed over time. For the Inventory, the calculated potential emissions are adjusted using data on reductions reported to the Natural Gas STAR program, and data on regulations that result in CH₄ reductions. The revisions in the current inventory (see Recalculations Discussion below) result in net emission approaches being used for many sources in the inventory.

The calculation of emissions from natural gas systems is outlined below:

Step 1. Calculate Potential Methane (or Net Methane) – Collect activity data on production and equipment in use and apply emission factors (i.e., scf gas per unit or activity)

Step 2. Compile Reductions Data – Calculate the amount of the methane that is not emitted, using data on voluntary action and regulations

Step 3. Calculate Net Emissions – Deduct methane that is not emitted from the total methane potential estimates to develop net CH₄ emissions, and calculate CO₂ emissions

Step 1. Calculate Potential Methane (or Net Methane)—Collect activity data on production and equipment in use and apply emission factors

In the first step, potential CH₄ is calculated by multiplying activity data (such as miles of pipeline or number of wells) by factors that relate that activity data to potential CH₄. Potential CH₄ is the amount of CH₄ that would be emitted in the absence of any control technology or mitigation activity. It is important to note that potential CH₄ factors in most cases do not represent emitted CH₄, and must be adjusted for any emissions-reducing technologies, or practices, as appropriate. For more information, please see the Annex.

Potential Methane Factors and Net Emission Factors

A primary basis for estimates of CH₄ and non-combustion-related CO₂ emissions from the U.S. natural gas industry is a detailed study by the Gas Research Institute (GRI) and EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 CH₄ emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The EPA/GRI study was based on a combination of process engineering studies, collection of activity data, and measurements at representative gas facilities conducted in the early 1990s. Methane compositions from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas

Composition Databases (GTI 2001) are adjusted year to year using gross production for oil and gas supply National Energy Modeling System (NEMS) regions from the EIA. Therefore, emission factors may vary from year to year due to slight changes in the CH₄ composition for each NEMS oil and gas supply module region. The emission factors used to estimate CH₄ were also used to calculate non-combustion CO₂ emissions. Data from GTI 2001 were used to adapt the CH₄ emission factors into non-combustion related CO₂ emission factors. Additional information about CO₂ content in transmission quality natural gas was obtained from numerous U.S. transmission companies to help further develop the non-combustion CO₂ emission factors.

Although the Inventory primarily uses EPA/GRI emission factors (especially for early years of the time series), EPA has made revisions to the potential factor methodology in the emissions estimates for several sources in recent Inventories. For gas well completions and workovers (refracturing) with hydraulic fracturing, EPA uses its Greenhouse Gas Reporting Program (GHGRP) Subpart W data to stratify the emission sources into four different categories and developed CH₄ emission factors for each category. For liquids unloading, EPA calculates national emissions through the use of region-specific emission factors developed from well data collected in a survey conducted by API/ANGA (API/ANGA 2012). In the current Inventory, EPA has used data generated by studies and the GHGRP to develop emission factors that are control category-specific (e.g., bleed rate-specific emission factors for pneumatic controllers in the production and transmission and storage segments) and to reflect current practices for activities (e.g., distribution M&R station emission factors for recent years). For these sources, the emission factors are not potential factors, but are instead factors for net emissions.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH₄ and non-combustion CO₂ emissions from natural gas systems.

Activity Data

Activity data were taken from the following sources: DrillingInfo, Inc (DrillingInfo 2015); American Gas Association (AGA 1991 through 1998); Bureau of Ocean Energy Management, Regulation and Enforcement (previous Minerals and Management Service) (BOEMRE 2011a, 2011b, 2011c, 2011d); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2015a, 2015b, 2015c); the Natural Gas STAR Program annual emissions savings (EPA 2013c); Oil and Gas Journal (OGJ 1997 through 2015); Pipeline and Hazardous Materials Safety Administration (PHMSA 2015a, 2015b); Federal Energy Regulatory Commission (FERC 2015); Greenhouse Gas Reporting Program (EPA 2015); other Energy Information Administration data and publications (EIA 2001, 2004, 2012, 2013, 2014); (EPA 1999); Conservation Commission (Wyoming 2015); and the Alabama State Oil and Gas Board (Alabama 2015).

For a few sources, recent direct activity data are not available. For these sources, either 2013 data was used as a proxy for 2014 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.

Step 2. Compile Reductions Data—Calculate the amount of the CH₄ that is not emitted, using data on voluntary action and regulations

The emissions calculated in Step 1 above for many sources represent potential emissions from an activity, and do not take into account use of technologies and practices that reduce emissions. To take into account use of such technologies, data, where available, are collected on both regulatory and voluntary reductions. Regulatory actions taken into account using this method include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents and condensate tanks. Voluntary reductions included in the Inventory are those reported to Natural Gas STAR. For more information on these reductions, please see Annex 3.6. The emission estimates presented in Table 3-46 and Table 3-47 are the CH₄ that is emitted to the atmosphere (i.e., net emissions), not potential emissions without capture or flaring.

The Inventory also includes the impacts of the New Source Performance Standards (NSPS) Subpart OOOO, which came into effect in October 2012. By separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific CH₄ emission factors for each category, EPA is implicitly accounting for Subpart OOOO reductions from hydraulically fractured gas wells. The method for calculating emissions from pneumatic controllers (by bleed rate category) also implicitly accounts for NSPS reductions in the high bleed pneumatic controller category.

The use of data from the EPA's GHGRP and recent studies to revise certain emission factors as discussed above obviated the need to apply Gas STAR or other reductions data for those sources (i.e., the calculated emissions were already net emissions, instead of potential emissions). More information is in the Recalculations Discussion below.

Step 3. Calculate Net Emissions—Deduct CH₄ that is not emitted from the total CH₄ potential estimates to develop net CH₄ emissions, and calculate CO₂ emissions

In the final step, emission reductions from voluntary and regulatory actions are deducted from the total calculated potential emissions to estimate the net emissions that are presented in Table 3-46, and included in the Inventory totals. As discussed above, for a number of categories (e.g., liquids unloading, condensate tanks, gas well completions and workovers with hydraulic fracturing, gathering stations, centrifugal compressors, pneumatic controllers, transmission and storage station fugitives, M&R stations, and pipeline leaks) emissions are calculated directly using emission factors that vary by technology or over time and account for any control measures in place that reduce CH₄ emissions.

Uncertainty and Time-Series Consistency

The most recent uncertainty analysis for the natural gas and petroleum systems emission estimates in the Inventory was conducted for the 1990 to 2009 Inventory report that was released in 2011. Since the analysis was last conducted, several of the methods used in the Inventory have changed, and industry practices and equipment have evolved. In addition, new studies (e.g., Lamb, et al. 2015; Lyon, et al. 2015; Marchese, et al. 2015; Zimmerle, et al. 2015) and other data sources such as those discussed in the sections below offer improvement to understanding and quantifying the uncertainty of some emission source estimates. EPA is planning an update to the uncertainty analysis conducted for the 2011 Inventory to reflect the new information. At this time, it is difficult to project whether updated uncertainty bounds around CH₄ emission estimates would be wider, tighter, or about the same as the current uncertainty bounds that were developed for the Inventory published in 2011 (i.e., minus 19 percent and plus 30 percent) given the extensive nature of these revisions.

Details on EPA's planned uncertainty analysis are described in the Planned Improvements section.

EPA conducted a quantitative uncertainty analysis for the 2011 Inventory to determine the level of uncertainty surrounding estimates of emissions from natural gas systems using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique). The @RISK software model was used to quantify the uncertainty associated with the emissions estimates using the 12 highest-emitting sources ("top 12 sources") for the year 2009. The @RISK 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 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 emissions estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The uncertainty analysis conducted for the 2011 Inventory has not yet been updated for this inventory; instead, EPA has applied the uncertainty percentage ranges calculated previously for 2009 to the 2014 emissions estimates. As discussed in the Recalculations Discussion section, EPA has used findings from multiple recently published studies along with GHGRP Subpart W data to revise the emission factors and activity data for many emission sources. Given these substantive revisions, it is unlikely that the 2009 uncertainty ranges applied will reflect the uncertainty associated with the recently revised emission factors and activity data sources. Details on an updated uncertainty analysis to reflect recent recalculations are described in the Planned Improvements section.

The results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall for the year 2014, based on the previously conducted uncertainty assessment using the recommended IPCC methodology. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-51. Natural gas systems CH₄ emissions in 2014 were estimated to be between 142.7 and 229.0 MMT CO₂ Eq. at a 95 percent confidence level, based on previously calculated uncertainty. Natural gas systems non-energy CO₂ emissions in 2014 were estimated to be between 34.3 and 55.1 MMT CO₂ Eq. at a 95 percent confidence level.

Table 3-51: Approach 2 Quantitative Uncertainty Estimates for CH₄ and Non-energy CO₂ Emissions from Natural Gas Systems (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.) ^b	Uncertainty Range Relative to Emission Estimate ^a (MMT CO ₂ Eq.) (%)			
			Lower Bound ^b	Upper Bound ^b	Lower Bound ^b	Upper Bound ^b
Natural Gas Systems	CH ₄	176.1	142.7	229.0	-19%	+30%
Natural Gas Systems ^c	CO ₂	42.4	34.3	55.1	-19%	+30%

^a Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2009.

^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 3-46 and Table 3-47.

^c An uncertainty analysis for the non-energy CO₂ emissions was not performed. The relative uncertainty estimated (expressed as a percent) from the CH₄ uncertainty analysis was applied to the point estimate of non-energy CO₂ emissions

EPA compared the quantitative uncertainty estimates for CH₄ emissions in recent years from natural gas systems to those reported in recently published studies (see “Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates” [EPA 2016a]).⁷³ All studies reviewed for uncertainty information used the Monte Carlo simulation technique to examine uncertainty bounds for the estimates reported which is in line with the IPCC recommended Approach 2 methodology. The uncertainty ranges in the reported studies differ from those of EPA. However, it is difficult to extrapolate uncertainty ranges from these studies to apply to the Inventory estimates because the Inventory source category level uncertainty analysis is not directly comparable to source- or segment-specific uncertainty analyses in these studies. Further, the methodologies and data sources used in estimating CH₄ emissions in these studies differ significantly from the studies underlying previous Inventory methodologies.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. 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 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. In addition, EPA receives feedback through annual expert and public review periods. Feedback received is noted in the Recalculations and Planned Improvement sections.

Recalculations Discussion

The EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories’ formal public notice periods, GHGRP data, and new studies. The EPA carefully evaluated relevant information available, and made several updates, including revisions to production segment activity data, production segment pneumatic controller activity and emissions data, gathering and boosting facility emissions, transmission and storage station activity and emissions data, distribution segment emissions data for pipelines, distribution segment M&R station activity and emissions data, and distribution segment customer meter emissions data.

⁷³ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

From December 2015 through February 2016, the EPA released four draft memoranda that discussed the changes under consideration and requested stakeholder feedback on those changes. See “Revisions under Consideration for Natural Gas and Petroleum Production Emissions,” “Revisions under Consideration for Gathering and Boosting Emissions,” “Revisions under Consideration for Transmission and Storage Emissions,” and “Revisions under Consideration for Distribution Emissions,” available at <https://www3.epa.gov/climatechange/ghgemi.../natural-gas-systems.html>.

The impact of all revisions to natural gas systems is an increase of 18 MMT CO₂ Eq., or 12 percent, comparing the 2013 value from last year’s Inventory to the current Inventory. Over the time series, the average change is an increase of 13 MMT CO₂ Eq., or 7 percent.

Recalculations for the production segment (including gathering and boosting facilities) resulted in a large increase in the 2013 CH₄ emission estimate, from 47.0 MMT CO₂ Eq. in the previous (2015) Inventory, to 110.7 MMT CO₂ Eq. in the current (2016) Inventory, or 136 percent. Over the time series, the average change is an increase of 35 MMT CO₂ Eq., or 57 percent.

Although there were no methodological updates to the processing segment, recalculations due to updated data (specifically data on national dry gas production in 2013, which were revised slightly downwards) impacted emissions estimates, resulting in a decrease of 0.1 MMT CO₂ Eq., or less than 1 percent comparing the 2013 value from last year’s Inventory to the current Inventory. Over the time series, the average change was less than 1 percent.

Recalculations for the transmission and storage segment resulted in a large decrease in the 2013 CH₄ emission estimate, from 54.4 MMT CO₂ Eq. in the previous (2015) Inventory, to 30.8 MMT CO₂ Eq. in the current (2016) Inventory, or 43 percent. Over the time series, the average change is a decrease of 13 MMT CO₂ Eq., or 25 percent.

Recalculations for the distribution segment also resulted in a large decrease in the 2013 CH₄ emission estimate, from 33.3 MMT CO₂ Eq. in the previous (2015) Inventory, to 11.5 MMT CO₂ Eq. in the current (2016) Inventory, or 65 percent. Over the time series, the average change is a decrease of 9 MMT CO₂ Eq., or 27 percent.

Production

This section references the final 2016 (current) Inventory production segment supporting memoranda: “Revisions to Natural Gas and Petroleum Production Emissions” and “Revisions to Natural Gas Gathering and Boosting Emissions” (EPA 2016b and EPA 2016c).⁷⁴ These memoranda contain further details and documentation of recalculations.

Using newly available GHGRP activity data, the EPA developed activity factors (i.e., counts per gas well) for in-line heaters, separators, dehydrators, compressors, meters/piping, pneumatic pumps, and pneumatic controllers. EPA reviewed this new data source and the previous data, assessed stakeholder feedback, and determined that the previous data source represents activities from the time period in which the data were collected (early 1990s) and the new GHGRP data source represents activities from recent years. The EPA applied the updated activity factors to calculate emissions from these sources for the years from 2011 to 2014 in the 2016 (current) Inventory natural gas production segment, while retaining the previous activity factors for 1990 to 1992. For years 1993 through 2010, the EPA calculated equipment counts by linearly interpolating between the data points of per well equipment counts in 1992 (based on GRI/EPA) and per well equipment counts in 2011 (based on GHGRP). This reflects an assumed gradual transition from the counts per well observed in the 1996 study and the counts observed in the recent GHGRP data.

The production segment activity data revisions not only reflect more current information on activity, but also tailor these emission sources to specifically reflect activity occurring at well pad facilities and not at gathering/centralized facilities. As discussed below and in the two supporting memoranda for the production segment, EPA has also implemented revisions to the gathering and boosting sub-segment so that equipment leaks from both types of facilities are fully, but separately, represented. In the public review draft, EPA noted potential issues with ensuring that vented emissions from certain equipment (e.g., pneumatic controllers, chemical injection pumps, dehydrator vents, and Kimray pumps) are not double-counted or inadvertently excluded due to these methodological revisions.

⁷⁴ See <<https://www3.epa.gov/climatechange/ghgemi.../natural-gas-systems.html>>.

The 2016 (current) Inventory methodology for these sources generally addresses this concern. Please refer to “Revisions to Natural Gas and Petroleum Production Emissions” for more information (EPA 2015b).

The impact of using activity factors developed from GHGRP data is an increase in emissions. This increase is shown in Table 3-52. For the year 2013, compared to the previous Inventory, the calculated CH₄ emissions increase due to use of revised activity factors for heaters, separators, dehydrators, compressors, and meters/piping is approximately 0.4 MMT CO₂ Eq. In addition, as dehydrator counts are an input to the calculation of emissions from the dehydrator vent and Kimray pump source, the revision to activity data impacted those estimates as well, resulting in a decrease of 2 MMT CO₂ Eq. for dehydrator vents, and 7 MMT CO₂ Eq. for Kimray pumps (comparing updated 2013 estimate to previous 2013 estimate). For chemical injection pumps, in addition to updating the activity data, emission factors were also recalculated using GHGRP data. This recalculation resulted in an increase in calculated emissions from chemical pumps for 2013 of 1.7 MMT CO₂ Eq., compared with the previous inventory estimate for 2013.

Table 3-52: CH₄ Emissions from Sources with Updates to use GHGRP Data (MMT CO₂ Eq.)

Type	Source	1990	2005	2010	2013	2014
Venting	Chemical Injection Pumps	0.7	2.4	3.3	3.2	3.2
	<i>Previous-Chemical</i>					
<i>Venting</i>	<i>Injection Pumps</i>	<i>0.7</i>	<i>1.4</i>	<i>1.6</i>	<i>1.5</i>	NA
Fugitive	Dehydrators	0.4	0.3	0.2	0.2	0.2
<i>Fugitive</i>	<i>Previous-Dehydrators</i>	<i>0.4</i>	<i>0.7</i>	<i>0.8</i>	<i>0.8</i>	NA
Fugitive	Separators	1.1	2.4	3.0	3.0	3.0
<i>Fugitive</i>	<i>Previous-Separators</i>	<i>1.1</i>	<i>2.1</i>	<i>2.6</i>	<i>2.6</i>	NA
Fugitive	Heaters	0.3	0.5	0.6	0.6	0.6
<i>Fugitive</i>	<i>Previous- Heaters</i>	<i>0.3</i>	<i>0.7</i>	<i>0.8</i>	<i>0.8</i>	NA
Fugitive	Meters/Piping	1.2	2.3	2.7	2.7	2.7
<i>Fugitive</i>	<i>Previous-Meters/Piping</i>	<i>1.3</i>	<i>2.2</i>	<i>2.7</i>	<i>2.6</i>	NA
Fugitive	Compressors	0.8	1.9	2.4	2.4	2.4
<i>Fugitive</i>	<i>Previous-Compressors</i>	<i>0.9</i>	<i>1.5</i>	<i>1.8</i>	<i>1.7</i>	NA

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

Using the GHGRP data, the EPA also developed technology-specific activity data and emission factors for pneumatic controllers. Reported data under the GHGRP allow for the development of pneumatic controller emission factors specific to bleed type (continuous high bleed, continuous low bleed, and intermittent bleed) and the associated break-out of activity data into these categories. These revised emission factors and bleed type-specific activity data reflect net emissions. Comparing the updated 2013 estimate to the previous Inventory 2013 estimate, the impact of using bleed type-specific emission factors and activity data developed from GHGRP data on pneumatic controller emissions is an increase of approximately 18.0 MMT CO₂ Eq., as shown in Table 3-53.

Table 3-53: CH₄ Emissions from Pneumatic Controllers (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
All	13.9	27.0	31.2	31.5	27.6
High bleed	+	12.1	10.9	4.8	3.3
Low bleed	8.4	0.6	1.1	0.6	1.0
Intermittent bleed	5.5	14.3	19.2	26.0	23.3
<i>Previous-All</i>	<i>13.4</i>	<i>20.2</i>	<i>16.2</i>	<i>13.5</i>	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

The 2015 Marchese et al. study assessed CH₄ emissions from an expanded universe of gathering stations compared with what was previously included in the Inventory. The Marchese et al. study analyzed emissions from five different types of gathering stations: compression only; compression and dehydration; compression, dehydration, and acid gas removal; dehydration only; and dehydration and acid gas removal. Previous Inventories estimated emissions from only gathering compression stations. In this Inventory, the EPA has applied a station-level emission factor and national activity estimates developed from the Marchese et al. data. See “Revisions to Natural Gas

Gathering and Boosting Emissions” for more information (EPA 2016c).⁷⁵ The impact of using revised activity data and emission factors for gathering stations cannot be straightforwardly determined based on the structure of previous Inventories (e.g., dehydrator emissions in previous inventories are not differentiated between well pad and gathering facility locations); however, due to the activity data revision alone, production segment emissions greatly increase compared to previous estimates. The station-level emission factor was applied to all years of the time series, and current activity data estimates were replaced with station counts based on the Marchese et al. estimate (scaled for earlier years based on national natural gas marketed production). Methane emissions from gathering and boosting are shown in Table 3-54.

Table 3-54: CH₄ Emissions from Gathering and Boosting (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
Gathering and Boosting Stations	23.9	27.7	35.8	43.3	46.6

The EPA’s approach for revising the Inventory methodology to incorporate GHGRP data and Marchese et al. data obviates the need to apply Gas STAR reductions data for certain sources in the production segment. EPA carried forward reported reductions for sources that are not being revised to use a net emission factor approach. There are also significant Gas STAR reductions in the production segment that are not classified as applicable to specific emission sources (“other voluntary reductions” are 18 MMT CO₂ Eq. of CH₄ in year 2014). To address potential double-counting of reductions, a scaling factor was applied to the “other voluntary reductions” to reduce this reported amount based on an estimate of the fraction of those reductions that occur in the sources that are now calculated using net emissions approaches. This fraction was developed by dividing the net emissions from sources with net emissions approaches, by the total production segment emissions (without deducting the Gas STAR reductions). The result for 2014, is that approximately 50 percent of the reductions were estimated to occur in sources for which net emissions are now calculated, which yields an adjusted “other voluntary reduction” number of 9 MMT CO₂ Eq.

Transmission and Storage

This section references the final 2016 (current) Inventory Transmission and Storage supporting memorandum: “Revisions to Natural Gas Transmission and Storage Emissions” (EPA 2016d).⁷⁶ This memorandum contains further details and documentation of recalculations.

For transmission and storage non-compressor fugitive emissions in the 2016 (current) Inventory, EPA used Zimmerle et al. data to develop the activity data for transmission stations (“Alternative” approach) and EIA data on active storage fields, along with the Zimmerle estimate of storage stations per storage field to develop storage station counts. The EPA then applied emission factors from Zimmerle et al. to calculate emissions for fugitives from these sources.

Interpolation was used to create time series consistency between earlier years’ emission factors (1990-1992) that generally rely on data from GRI/EPA 1996 and the Zimmerle et al. emission factors for recent years. However, the station fugitive emission factors in previous Inventories included station fugitives but not compressor fugitives, and separate emission factors were applied for compressor emissions (including compressor fugitive and vented sources). Because Zimmerle et al. grouped compressor fugitives with station fugitives, the two sets of emission factors (GRI/EPA and Zimmerle et al.) cannot be directly compared. Therefore in the 2016 (current) Inventory, the EPA calculated total station-level emission factors for transmission and storage stations that include station and compressor fugitive sources as well as compressor vented sources.

In the 2016 (current) Inventory, the EPA incorporated Zimmerle et al. national population estimates of reciprocating and centrifugal compressor activity data, along with the GHGRP break out between centrifugal compressor seal types (wet versus dry seals), and Zimmerle et al. emission factor data, in development of emission estimates for compressors in transmission and storage.

⁷⁵ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

⁷⁶ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

In order to create time series consistency between earlier years' compressor count estimates (1990 to 1992) and the most recent years' compressor count estimates (2012 to 2014) that were calculated from Zimmerle et al. and GHGRP data, compressor counts for the years 1993 through 2011 were calculated using linear interpolation between the data endpoints of 1992 and 2012.

The overall impact of using revised emissions data and activity data from Zimmerle et al. and GHGRP is a decrease in emissions for station fugitives and compressors. For the year 2013, the CH₄ emissions decrease due to use of revised emission factors and activity data for transmission and storage station fugitives and compressor venting is approximately 18.4 MMT CO₂ Eq. Methane emissions from transmission stations are shown in Table 3-55, while methane emissions from storage stations are shown in Table 3-56.

Table 3-55: CH₄ Emissions from Transmission Stations (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
Station Total Emissions	27.5	16.7	13.0	13.4	14.3
Station + Compressor					
Fugitive Emissions	NA	NA	NA	2.7	2.9
Reciprocating Compressor	NA	NA	NA	7.9	8.5
Centrifugal Compressor (wet seals)	NA	NA	NA	1.4	1.5
Centrifugal Compressor (dry seals)	NA	NA	NA	1.3	1.4
Previous-Station Total	27.5	28.1	28.5	28.3	NA
<i>Previous-Station Fugitives^a</i>	2.7	2.8	2.8	2.8	NA
<i>Previous-Reciprocating Compressor^a</i>	<i>18.6</i>	<i>19.2</i>	<i>19.4</i>	<i>19.3</i>	<i>NA</i>
<i>Previous-Centrifugal Compressor (wet seals)^a</i>	<i>6.2</i>	<i>5.9</i>	<i>5.9</i>	<i>5.8</i>	<i>NA</i>
<i>Previous-Centrifugal Compressor (dry seals)^a</i>	<i>+</i>	<i>0.3</i>	<i>0.4</i>	<i>0.4</i>	<i>NA</i>

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

*These values from the previous inventory cannot be compared to the estimates in this Inventory as the source categories have different definitions in their respective data sources (e.g., one includes certain fugitives, one does not).

Note: Values in *italics* are from the previous Inventory.

Table 3-56: CH₄ Emissions from Storage Stations (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
Station Total Emissions	6.1	4.1	3.5	3.3	3.3
Station + Compressor					
Fugitive Emissions	NA	NA	NA	0.6	0.6
Reciprocating Compressor	NA	NA	NA	2.7	2.7
Centrifugal Compressor (wet seals)	NA	NA	NA	NA	NA
Centrifugal Compressor (dry seals)	NA	NA	NA	NA	NA
Previous-Station Total	6.1	6.7	6.6	6.8	NA
<i>Previous-Station Fugitives^a</i>	<i>1.4</i>	<i>1.5</i>	<i>1.5</i>	<i>1.5</i>	<i>NA</i>
<i>Previous-Reciprocating Compressor^a</i>	<i>3.9</i>	<i>4.3</i>	<i>4.3</i>	<i>4.4</i>	<i>NA</i>
<i>Previous-Centrifugal Compressor (wet seals)^a</i>	<i>0.8</i>	<i>0.8</i>	<i>0.7</i>	<i>0.6</i>	<i>NA</i>
<i>Previous-Centrifugal Compressor (dry seals)^a</i>	<i>+</i>	<i>0.1</i>	<i>0.2</i>	<i>0.3</i>	<i>NA</i>

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

* These values from the previous inventory cannot be compared to the estimates in this Inventory as the source categories have different definitions in their respective data sources (e.g., one includes certain fugitives, one does not).

Note: Values in *italics* are from the previous Inventory.

In the 2016 (current) Inventory, the transmission and storage pneumatic controller emissions have been calculated using the GHGRP data on controllers per station and emission factors. The overall impact of using revised emissions data and activity data from GHGRP was a decrease in emissions from transmission station pneumatic controllers and a slight decrease in emissions from storage station pneumatic controllers for recent time series years. For the year 2013, the CH₄ emissions decrease due to use of revised emission factors and activity data for transmission and storage station pneumatic controllers is 5.0 MMT CO₂ Eq. Methane emissions from transmission segment pneumatic controllers are shown in Table 3-57, while methane emissions from storage segment pneumatic controllers are shown in Table 3-58.

In order to create time series consistency between earlier years' pneumatic controller data (1990 to 1992) and the most recent years' data (2011 to 2014) when populating intermediate years, the EPA retained counts and estimates of weighted average emissions per controller in early years, then linearly interpolated the total count and weighted average emissions per controller in year 2011.

Table 3-57: CH₄ Emissions from Transmission Segment Pneumatic Controllers (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
All	5.3	1.8	0.9	0.7	0.7
High bleed	NA	NA	NA	0.3	0.3
Low bleed	NA	NA	NA	0.3	0.4
Intermittent bleed	NA	NA	NA	+	+
Previous-All	<i>5.3</i>	<i>5.2</i>	<i>5.3</i>	<i>5.2</i>	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

Table 3-58: CH₄ Emissions from Storage Segment Pneumatic Controllers (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
All	1.1	0.9	0.7	0.8	0.7
High bleed	NA	NA	NA	0.6	0.6
Low bleed	NA	NA	NA	0.1	0.1
Intermittent bleed	NA	NA	NA	+	+
Previous-All	<i>1.1</i>	<i>1.2</i>	<i>1.2</i>	<i>1.3</i>	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

The EPA's approach for revising the inventory methodology to incorporate Zimmerle et al. and GHGRP data in the transmission and storage segment resulted in net emissions being directly calculated for revised sources in each time series year. This obviated the need to apply Gas STAR reductions data for these sources. Previous Inventories have applied Gas STAR reductions to other specific transmission and storage segment sources including compressor engine and pipeline venting. EPA carried forward reported reductions for these sources since they are not being revised to use a net emission factor approach. There are also Gas STAR reductions in the transmission and storage segment that are not classified as applicable to specific emission sources ("other voluntary reductions" are 3.6 MMT CO₂ Eq. CH₄ in year 2013). Some portion of the "other voluntary reductions" might apply to the emission sources for which the EPA has revised the methodology to use a net emission factor approach. The EPA is investigating potential disaggregation of "other voluntary reductions." The EPA has retained Gas STAR reductions classified as "other voluntary reductions," without adjustment, in the 2016 (current) Inventory.

Distribution

This section references the final 2016 (current) Inventory Distribution supporting memorandum: “Revisions to Natural Gas Distribution Emissions” (EPA 2016e).⁷⁷ This memorandum contains further details and documentation of recalculations.

For metering and regulating (M&R) stations, for the years from 2011 to 2014, in the 2016 (current) Inventory, the EPA used GHGRP reported activity data for counts of above ground and below ground stations. The EPA scaled the GHGRP station counts to the national level based on the miles of distribution pipeline main reported by GHGRP reporters, compared to the PHMSA national total miles of distribution pipeline main. The EPA then applied the existing inventory (from GRI) break out of station inlet pressure categories to the scaled counts of above ground and below ground M&R stations, and the station-level emission factors from Lamb et al. For years from 1990 to 2010, EPA used the previous inventory activity data for station counts. EPA used linear interpolation between GRI/EPA emission factors in early years (1990 to 1992) and Lamb et al. emission factors in recent years (2011 to 2014) for M&R stations.

For the year 2013, the M&R stations CH₄ emissions decrease due to use of revised emission factors and activity data is approximately 13.6 MMT CO₂ Eq. Methane emissions from M&R stations are shown in Table 3-59.

Table 3-59: CH₄ Emissions from M&R Stations (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
M&R	10.5	4.9	1.1	0.9	0.7
<i>Previous--M&R</i>	<i>8.2</i>	<i>9.1</i>	<i>9.0</i>	<i>9.3</i>	NA
R-Vault	+	0.1	0.1	+	+
<i>Previous--R-Vault</i>	<i>+</i>	<i>+</i>	<i>+</i>	<i>+</i>	NA
Reg	6.3	2.8	0.6	0.4	0.3
<i>Previous--Reg</i>	<i>4.9</i>	<i>5.4</i>	<i>5.4</i>	<i>5.6</i>	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

For pipeline leaks, in the 2016 (current) Inventory, the EPA used the previous activity data sources for miles of pipeline by material (PHMSA) and for leaks per mile (GRI), and Lamb et al., data on emissions per leak for recent years of the time series. For the year 2013, the pipeline leaks CH₄ emissions decrease due to use of revised emission factors is approximately 9.2 MMT CO₂ Eq. Methane emissions from pipeline leaks are shown in Table 3-60.

EPA used linear interpolation between GRI/EPA emission factors in early years (1990 to 1992) and Lamb et al. emission factors in recent years (2011 to 2014) for pipeline leaks.

Table 3-60: CH₄ Emissions from Pipeline Leaks (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
Mains	14.7	6.7	4.5	3.9	3.8
<i>Previous--Mains</i>	<i>14.7</i>	<i>11.8</i>	<i>11.3</i>	<i>10.7</i>	NA
Services	8.2	4.0	2.6	2.2	2.1
<i>Previous--Services</i>	<i>8.2</i>	<i>6.2</i>	<i>5.1</i>	<i>4.6</i>	NA

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

In the 2016 (current) Inventory, the EPA revised the emission factors for residential customer meters and commercial/ industrial customer meters. The EPA recalculated the residential customer meter emission factor by combining data from the 1996 GRI/EPA study (basis for previous Inventory emission factor) with more recent data from a GTI 2009 study and Clearstone 2011 study. The EPA weighted emission factors developed in each study by the number of meters surveyed in each study to develop the revised emission factor. In the 2016 (current) Inventory, the EPA applied the GTI 2009 commercial customer meter emission factor to the total count of commercial and

⁷⁷ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

industrial meters in the GHG Inventory. In addition, the EPA used an updated data source, identified by commenters on the public review Distribution memorandum for national customer meter counts (EIA data); previously, national customer meter counts were scaled from a 1992 base year value, but are now available directly for every year of the time series from EIA. For the year 2013, the customer meters CH₄ emissions increase due to use of revised emission factors and activity data is approximately 0.3 MMT CO₂ Eq. Methane emissions from customer meters are shown in Table 3-61.

For pipeline blowdowns and mishaps/dig-ins, the previous Inventories used base year 1992 distribution main and service miles and scaled the value for non-1992 years using relative residential gas consumption. However, scaling mileage based on residential gas consumption introduced volatility across the time series that does not likely correlate to pipeline mileage trends (as gas consumption is affected by other factors such as equipment efficiency and climate). In the 2016 (current) Inventory, the EPA used PHMSA data directly for the activity data in each time series year. The overall impact of using the revised activity data for pipeline blowdowns and mishaps/dig-ins is an increase in emissions. For the year 2013, the pipeline blowdowns CH₄ emissions increase due to use of revised activity data is approximately 0.04 MMT CO₂ Eq.; and for mishaps/dig-ins is approximately 0.6 MMT CO₂ Eq. Methane emissions from pipeline blowdown and mishaps/dig-ins are shown in Table 3-61.

Table 3-61: CH₄ Emissions for Other Distribution Sources (MMT CO₂ Eq.)

Source	1990	2005	2010	2013	2014
Residential Meters	1.5	1.9	1.9	2.0	2.0
<i>Previous--Residential Meters</i>	<i>2.6</i>	<i>2.8</i>	<i>2.8</i>	<i>2.9</i>	NA
Commercial/Industry Meters	1.1	1.3	1.3	1.4	1.4
<i>Previous--Commercial/Industry Meters</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	NA
Pressure Relief Valve Releases	+	+	+	+	+
<i>Previous--Pressure Relief Valve Releases</i>	<i>+</i>	<i>+</i>	<i>+</i>	<i>+</i>	NA
Pipeline Blowdowns	0.1	0.1	0.1	0.1	0.1
<i>Previous--Pipeline Blowdown</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	<i>0.1</i>	NA
Mishaps (Dig-ins)	1.2	1.5	1.6	1.6	1.7
<i>Previous--Mishaps (Dig-ins)</i>	<i>0.9</i>	<i>1.0</i>	<i>1.0</i>	<i>1.0</i>	NA

+ Does not exceed 0.05 MMT CO₂ Eq.

NA – Not applicable

Note: Values in *italics* are from the previous Inventory.

The EPA's approach for revising the Inventory methodology to incorporate Lamb et al. and subpart W data in the distribution segment resulted in net emissions being directly calculated for M&R stations, pipeline leaks, and customer meters in each time series year. This obviates the need to apply Gas STAR reductions data for these sources. Previous Inventories have also applied Gas STAR reductions to mishaps/dig-ins. EPA carried forward reported reductions for this source since it is not being revised to use a net emission factor approach. There are also Gas STAR reductions in the distribution segment that are not classified as applicable to specific emission sources (“other voluntary reductions” are 1.0 MMT CO₂ Eq. CH₄ in year 2013). Some portion of the “other voluntary reductions” might apply to the emission sources for which the EPA has revised methodology to use a net emission factor approach. The EPA is investigating potential disaggregation of “other voluntary reductions.” The EPA has retained Gas STAR reductions classified as “other voluntary reductions” unadjusted in the 2016 (current) Inventory.

Planned Improvements

Production Segment Estimates

In response to the public review draft and earlier released memorandum outlining potential revisions to the production and gathering and boosting segment, EPA received feedback from stakeholders that will be further considered to refine future Inventories.

In the production segment, some commenters suggested that the approach taken overestimates equipment counts in the production segment, while others suggested that the approach was appropriate. The EPA will further consider

how activity factors developed from GHGRP data may over- or under-represent equipment counts for non-GHGRP facilities (those not meeting the emissions reporting threshold). Preliminary assessment by EPA of this issue by disaggregating GHGRP reporter data by number of wells reported indicated that reporters with fewer wells had higher equipment counts per well than average. EPA will continue to explore other methods to assess whether the non-GHGRP population may have different average equipment counts than the reporting population and how this may be reflected in the Inventory. The EPA will also consider calculation of activity factors from GHGRP data (equipment and pneumatic controller counts per well) on a more granular basis, such as by geologic basin. EPA will continue to consider stakeholder feedback on the methodology used to develop counts of active wells (non-associated gas wells and gas wells with hydraulic fracturing) across the time series.

In response to the public review memoranda, EPA also received feedback from stakeholders on aspects of emission sources that were not significantly revised in the 2016 (current) Inventory. Stakeholders noted that data generated by Allen et al. in recent studies of pneumatic controller emissions in the production segment might be used to develop a separate emission factor for malfunctioning devices (in addition to the bleed type-specific factors developed from GHGRP data and used in the 2016 (current) Inventory). Stakeholders also recommended further investigating the emissions estimation methodology for gathering pipeline emissions, as the current factor is based on leak measurements from distribution mains conducted in the early 1990s. EPA will evaluate available data studies on this emission sources, and also take into account material-specific gathering pipeline activity data that will be available through the GHGRP.

EPA is considering updates to its estimates for liquids unloading. Data from a 2012 report published by the American Petroleum Institute (API) and America's Natural Gas Alliance (ANGA) were used to develop regional activity data and regional emission factors for gas well liquids unloading activities for Natural Gas Systems. EPA is considering how data from GHGRP and/or Allen et al. (2014a) can be used to update the Inventory estimates for this source.⁷⁸ Some commenters supported the use of scaled-up GHGRP data to calculate emissions from this source. Using the general scale up approach used for other production sources gives an approximation of a national estimate of 10 MMT CO₂ Eq. for 2013 (4.6 MMT CO₂ Eq. was reported from liquids unloading in 2013, from a total reported 208,991 wellheads estimated to be in the natural gas segment. The Inventory national well count total for 2013 is 454,491), compared with 6.5 MMT CO₂ Eq. in the current inventory.

EPA received mixed feedback on the update for gathering stations, with some commenters supporting the use of the Marchese et al. data, and others not supporting the update and recommending waiting for GHGRP data to update emissions from this source. Additionally, commenters recommended that EPA separate out emissions from gathering and boosting facilities from those from field production sites and noted that upcoming studies and GHGRP data may inform emissions estimates from this source. In the 2016 (current) Inventory, the EPA has presented gathering facility and gathering pipeline emissions as a “Gathering and Boosting” subsegment within the production segment; EPA will continue to consider how these sources may be presented in future Inventories. To address potential double counting, condensate storage tanks might be disaggregated between well pad facilities and gathering facilities in future Inventories. Stakeholder feedback included suggestions on how data from the Marchese et al. study and GHGRP data might be used, which EPA will consider for next year’s inventory. One commenter suggested that the potential overlap count be estimated to be 3.4 percent of the emissions from condensate tanks.

Processing Estimates

Commenters recommended consideration of recent data sources (Marchese et al. 2015 and GHGRP) for revisions to gas processing segment estimates. Commenters had mixed feedback on these data sources with some commenters supporting use of Marchese et al. and other supporting use of GHGRP data.

⁷⁸ Please see the memorandum “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Revisions to Liquids Unloading Estimates” (EPA 2015e) available at <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>

Transmission and Storage Estimates

In response to the public review memorandum outlining potential revisions to the transmission and storage segment, EPA received feedback from stakeholders that will be further considered to refine implementation of the 2016 revisions in future Inventories and to implement additional revisions. The EPA will consider approaches to developing average emission factors that integrate data from both recent studies and subpart W data. The EPA will seek more data to support or replace the Zimmerle et al. study assumption of 0.89 storage stations per field. The EPA will take into account findings emerging from ongoing research efforts by groups such as API (to better characterize emissions from pneumatic controllers) and Pipeline Research Council International (to analyze subpart W data). The EPA will also investigate potential revisions to certain emission sources not addressed in recent revisions but highlighted by commenters, including reciprocating compressor engines and storage tank dump valves.

In fall of 2015, a well in a California storage field began leaking methane at an estimated rate of 50 tons of CH₄ per day. The well was permanently sealed in February of 2016. EPA plans to include 2015 emissions from this source in next year's inventory (2017 report covering 1990 to 2015 emissions). EPA will review and potentially incorporate estimates of emissions from the leak, such as estimates developed by the California Air Resources Board (CARB). For information on CARB estimates, see http://www.arb.ca.gov/research/aliso_canyon_natural_gas_leak.htm.

Distribution Estimates

In response to the public review memorandum outlining potential revisions to the distribution segment, EPA received feedback from stakeholders that will be further considered to refine implementation of the 2016 revisions in future Inventories and to implement additional revisions. The EPA will assess differences between the Lamb et al. study and characteristics of the GHGRP population. The EPA will consider current interpolation approaches to use GRI factors later into the time series (e.g., if information is received indicating a specific time frame for the transition to lower-emitting equipment and practices). The EPA will assess whether available data support methodological revisions to differentiate new versus vintage plastic pipelines in the Inventory. The EPA will assess any new data on commercial or industrial meters to potentially improve the current emission factor. While most commenters supported updates to this segment, several commenters did not, referring to top down (e.g., tall tower) studies indicating the emissions may be higher than previously estimated, not lower. The EPA will continue to assess new top down and bottom up data in this segment.

Upcoming new data

GHGRP

Beginning in March 2016, GHGRP reporters will report data for gathering facilities over the GHGRP reporting threshold. The EPA will consider use of this data to update its estimates in the Inventory.

Commenters on recent Inventory drafts have recommended that EPA analyze and screen GHGRP data and exclude or correct outliers. Commenters have also recommended use of only measured GHGRP data in some cases. The EPA plans to continue reviewing data reported to its GHGRP for potential updates to data and methodology across all segments of natural gas systems.

Methane Challenge

In March 2016, EPA launched the Methane Challenge Program, through which oil and gas companies can make and track ambitious commitments to reduce methane emissions. 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.

Other Updates

EPA is evaluating several other sources for potential updates to future Inventories.

Abandoned wells are not currently accounted for in the Inventory. EPA is seeking appropriate emission factors and national activity data available to calculate these emissions. Commenters supported including this source category, noted the currently data is limited, and suggested reviewing data that will become available in the future.

The EPA continues to seek stakeholder feedback on natural gas systems super-emitter sources. The EPA will continue reviewing studies that could support potential revisions to inventory estimates, such as information from the Barnett Shale Campaign (e.g., Zavala et al. 2015). Several commenters noted superemitters detected and modeled in the Zimmerle et al. study but not incorporated into the inventory revision. In Zimmerle et al., superemitters were estimated to contribute 2.5 MMT CO₂ Eq. emissions to the study total estimate of emissions transmission and storage sources. The EPA will consider how unassigned superemitter emissions could be incorporated into the Inventory. EPA received mixed feedback on this issue with some commenters urging EPA to incorporate an estimate for superemitters, and others stating that inclusion of an estimate of unassigned superemitter emissions would be inappropriate and could result in double counting.

Uncertainty

As discussed in the Recalculations Discussion section above, EPA made several revisions in the 2016 (current) Inventory using information provided in recently published studies and the GHGRP Subpart W data, primarily including revisions to: production segment major equipment activity data, production segment pneumatic controller activity and emissions data, gathering and boosting facility activity and emissions data, transmission and storage station activity and emissions data, distribution pipelines emissions data, distribution M&R station activity and emissions data, and distribution customer meter emissions data. As noted in the Uncertainty section above, EPA has not yet updated its uncertainty analysis to reflect this new information. At the present time, it is difficult to project whether updated uncertainty bounds around CH₄ emission estimates would be wider, tighter, or about the same as the current uncertainty bounds that were developed for the Inventory published in 2011 (i.e., minus 19 percent and plus 30 percent) given the extensive nature of these revisions.

To update its uncertainty analysis, EPA will conduct a formal quantitative uncertainty analysis similar to that conducted for the 2011 Inventory using the IPCC-recommended Approach 2 methodology (Monte Carlo Simulation technique) using new data and taking into account stakeholder input received. For more information, please see the Uncertainty Memorandum (EPA 2016a). As in the 2011 Inventory analysis, EPA will first identify a select number of top-emitting emission sources for each source category. Note that to compile the top-emitting list of emission sources for natural gas systems, individual emission sources were analyzed at the NEMS region level for the production segment (because certain emission factors vary by region for many production sources), and at the national level for other segments. EPA is considering removing the NEMS region disaggregation in future Inventories, and potentially replacing it with a different level of disaggregation, such as at the sub-basin level. Refer to “Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty (EPA 2016a) for more information on planned improvements regarding uncertainty.⁷⁹.

3.8 Energy Sources of Indirect Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, many energy-related activities generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH₄ volatile organic compounds (NMVOCs) from energy-related activities from 1990 to 2014 are reported in Table 3-62.

Table 3-62: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
NO _x	21,106	16,602	12,004	11,796	11,051	10,557	9,995

⁷⁹ See <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

Mobile Combustion	10,862	10,295	7,290	7,294	6,788	6,283	5,777
Stationary Combustion	10,023	5,858	4,092	3,807	3,567	3,579	3,522
Oil and Gas Activities	139	321	545	622	622	622	622
Waste Combustion	82	128	77	73	73	73	73
<i>International Bunker Fuels^a</i>	<i>1,956</i>	<i>1,704</i>	<i>1,790</i>	<i>1,553</i>	<i>1,398</i>	<i>1,139</i>	<i>1,138</i>
CO	125,640	64,985	45,148	44,088	42,273	40,459	38,643
Mobile Combustion	119,360	58,615	39,475	38,305	36,491	34,676	32,861
Stationary Combustion	5,000	4,648	4,103	4,170	4,170	4,170	4,169
Waste Combustion	978	1,403	1,084	1,003	1,003	1,003	1,003
Oil and Gas Activities	302	318	487	610	610	610	610
<i>International Bunker Fuels^a</i>	<i>103</i>	<i>133</i>	<i>136</i>	<i>137</i>	<i>133</i>	<i>129</i>	<i>135</i>
NMVOCs	12,620	7,191	7,464	7,759	7,449	7,139	6,830
Mobile Combustion	10,932	5,724	4,591	4,562	4,252	3,942	3,632
Oil and Gas Activities	554	510	2,205	2,517	2,517	2,517	2,517
Stationary Combustion	912	716	576	599	599	599	599
Waste Combustion	222	241	92	81	81	81	81
<i>International Bunker Fuels^a</i>	<i>57</i>	<i>54</i>	<i>56</i>	<i>51</i>	<i>46</i>	<i>41</i>	<i>42</i>

^a These values are presented for informational purposes only and are not included in totals.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2014 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Emission estimates for 2012, 2013, and 2014 for non-EGU and non-mobile sources are held constant from 2011 in EPA (2015). 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

3.9 International Bunker Fuels (IPCC 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.⁸⁰ 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).⁸¹

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.⁸² Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO₂, CH₄ and N₂O for marine transport modes, and CO₂ and N₂O 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 IPCC guidelines distinguish between different modes of air traffic. 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 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 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 aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.⁸³

Emissions of CO₂ from aircraft are essentially a function of fuel use. 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 CH₄ is emitted by modern engines (Anderson et al. 2011), and as a result, CH₄ emissions from this category are considered zero. In jet engines, N₂O 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 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 2014 from the combustion of international bunker fuels from both aviation and marine activities were 104.2 MMT CO₂ Eq., or 0.3 percent below emissions in 1990 (see Table 3-63 and Table 3-64). Emissions from international flights and international shipping voyages departing from the United States have increased by 82.5 percent and decreased by 48.4 percent, respectively, since 1990. The majority of these emissions were in the form of CO₂; however, small amounts of CH₄ (from marine transport modes) and N₂O were also emitted.

Table 3-63: CO₂, CH₄, and N₂O Emissions from International Bunker Fuels (MMT CO₂ Eq.)

Gas/Mode	1990	2005	2010	2011	2012	2013	2014
CO ₂	103.5	113.1	117.0	111.7	105.8	99.8	103.2
Aviation	38.0	60.1	61.0	64.8	64.5	65.7	69.4
<i>Commercial</i>	30.0	55.6	57.4	61.7	61.4	62.8	66.3
<i>Military</i>	8.1	4.5	3.6	3.1	3.1	2.9	3.1
Marine	65.4	53.0	56.0	46.9	41.3	34.1	33.8
CH ₄	0.2	0.1	0.1	0.1	0.1	0.1	0.1

⁸⁰ 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).

⁸¹ Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

⁸² 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).

⁸³ Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

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
N₂O	0.9	1.0	1.0	1.0	0.9	0.9	0.9
Aviation	0.4	0.6	0.6	0.6	0.6	0.6	0.7
Marine	0.5	0.4	0.4	0.4	0.3	0.2	0.2
Total	104.5	114.2	118.1	112.8	106.8	100.7	104.2

^aCH₄ emissions from aviation are estimated to be zero.

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-64: CO₂, CH₄, and N₂O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2010	2011	2012	2013	2014
CO ₂	103,463	113,139	116,992	111,660	105,805	99,763	103,201
Aviation	38,034	60,125	60,967	64,790	64,524	65,664	69,411
Marine	65,429	53,014	56,025	46,870	41,281	34,099	33,791
CH ₄	7	5	6	5	4	3	3
Aviation ^a	0	0	0	0	0	0	0
Marine	7	5	6	5	4	3	3
N ₂ O	3	3	3	3	3	3	3
Aviation	1	2	2	2	2	2	2
Marine	2	1	1	1	1	1	1

^aCH₄ emissions from aviation are estimated to be zero.

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-65: Aviation CO₂ and N₂O Emissions for International Transport (MMT CO₂ Eq.)

Aviation Mode	1990	2005	2010	2011	2012	2013	2014
Commercial Aircraft	30.0	55.6	57.4	61.7	61.4	62.8	66.3
Military Aircraft	8.1	4.5	3.6	3.1	3.1	2.9	3.1
Total	38.0	60.1	61.0	64.8	64.5	65.7	69.4

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology

Emissions of CO₂ were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1 – CO₂ from Fossil Fuel Combustion. Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil were taken directly from EIA 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 (2016) and USAF (1998), and heat content for jet fuel was taken from EIA (2016). 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 CH₄ and N₂O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH₄ and N₂O emissions were obtained from the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.1 for N₂O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.32 for CH₄ and 0.08 for N₂O. 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, 2000 through 2014 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 CO₂ estimates for 1990 and 2000 through 2014 are obtained from FAA's AEDT model (FAA 2016). The radar-informed method that was used to estimate CO₂ emissions for commercial aircraft for 1990, and 2000 through 2014 is not possible for 1991 through 1999 because the radar data set is not available for years prior to 2000. FAA developed OAG schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. Because fuel consumption and CO₂ 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.

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 2015). 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 3-66. See Annex 3.8 for additional discussion of military data.

Activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were taken from unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 2015) for 1990 through 2001, 2007 through 2014, 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 (2015). 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 3-67.

Table 3-66: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	2005	2010	2011	2012	2013	2014
U.S. and Foreign Carriers	3,222	5,983	6,173	6,634	6,604	6,748	7,126
U.S. Military	862	462	367	319	321	294	318
Total	4,084	6,445	6,540	6,953	6,925	7,042	7,445

Note: Totals may not sum due to independent rounding.

Table 3-67: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2010	2011	2012	2013	2014
Residual Fuel Oil	4,781	3,881	4,141	3,463	3,069	2,537	2,466
Distillate Diesel Fuel & Other	617	444	476	393	280	235	261
U.S. Military Naval Fuels	522	471	448	382	381	308	331
Total	5,920	4,796	5,065	4,237	3,730	3,081	3,058

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.⁸⁴ 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, and in the activity data on military operations and training that were used to estimate percentages of total fuel use reported as bunker fuel emissions. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the Navy and Air Force from the Defense Logistics Agency. These data may slightly over or under estimate actual total fuel use in aircraft and ships because each Service may have procured fuel from, and/or may have sold to, traded with, and/or given fuel to other ships, aircraft, governments, or other entities. There are uncertainties in 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 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 2001. 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, Department and military Service 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 additional data collection.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO₂ 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

⁸⁴ See uncertainty discussions under Carbon Dioxide Emissions from Fossil Fuel Combustion.

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 CO₂.⁸⁵

There is also concern regarding the reliability of the existing DOC (2015) 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for international bunker fuels was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO₂, CH₄, and N₂O 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.

Planned Improvements

The feasibility of including data from a broader range of domestic and international sources for bunker fuels, including data from studies such as the Third IMO GHG Study 2014, is being considered.

3.10 Wood Biomass and Ethanol Consumption (IPCC Source Category 1A)

The combustion of biomass fuels such as wood, charcoal, and wood waste and biomass-based fuels such as ethanol generates CO₂ in addition to CH₄ and N₂O already covered in this chapter. In line with the reporting requirements for inventories submitted under the UNFCCC, CO₂ emissions from biomass combustion have been estimated separately from fossil fuel CO₂ 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 (C) 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 CO₂ emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

In 2014, total CO₂ emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 217.7 MMT CO₂ Eq. (217,654 kt) (see Table 3-68 and Table 3-69). As the largest consumer of woody biomass, the industrial sector was responsible for 57.1 percent of the CO₂ emissions from this source. The residential sector was the second largest emitter, constituting 27.5 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

⁸⁵ U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site, 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. The estimates in Mobile Combustion are also likely to include emissions from ocean-going vessels departing from U.S. ports on international voyages.

Table 3-68: CO₂ Emissions from Wood Consumption by End-Use Sector (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Industrial	135.3	136.3	119.5	122.9	125.7	123.1	124.4
Residential	59.8	44.3	45.4	46.4	43.3	59.8	59.8
Commercial	6.8	7.2	7.4	7.1	6.3	7.2	7.6
Electricity Generation	13.3	19.1	20.2	18.8	19.6	21.4	25.9
Total	215.2	206.9	192.5	195.2	194.9	211.6	217.7

Note: Totals may not sum due to independent rounding.

Table 3-69: CO₂ Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Industrial	135,348	136,269	119,537	122,865	125,724	123,149	124,369
Residential	59,808	44,340	45,371	46,402	43,309	59,808	59,808
Commercial	6,779	7,218	7,385	7,131	6,257	7,235	7,569
Electricity Generation	13,252	19,074	20,169	18,784	19,612	21,389	25,908
Total	215,186	206,901	192,462	195,182	194,903	211,581	217,654

Note: Totals may not sum due to independent rounding.

The transportation sector is responsible for most of the ethanol consumption in the United States. Ethanol 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 2014, the United States consumed an estimated 1,111.3 trillion Btu of ethanol, and as a result, produced approximately 76.1 MMT CO₂ Eq. (76,075 kt) (see Table 3-70 and Table 3-71) of CO₂ emissions. Ethanol 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 3-70: CO₂ Emissions from Ethanol Consumption (MMT CO₂ Eq.)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation ^a	4.1	22.4	71.3	71.5	71.5	73.4	74.8
Industrial	0.1	0.5	1.1	1.1	1.1	1.2	1.0
Commercial	+	0.1	0.2	0.2	0.2	0.2	0.3
Total	4.2	22.9	72.6	72.9	72.8	74.7	76.1

^a Does not exceed 0.05 MMT CO₂ Eq.^a See Annex 3.2, Table A-94 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Table 3-71: CO₂ Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation ^a	4,136	22,414	71,287	71,537	71,510	73,359	74,810
Industrial	56	468	1,134	1,146	1,142	1,202	987
Commercial	34	60	226	198	175	183	277
Total	4,227	22,943	72,647	72,881	72,827	74,743	76,075

^a See Annex 3.2, Table A-94 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2016) (see Table 3-72), provided in energy units for the industrial, residential, commercial, and electric generation 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. It was assumed that the woody biomass contains black liquor and other wood wastes, has a moisture content of 12 percent, and is converted into CO₂ with 100 percent efficiency. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/QBtu (EPA 2010) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2016) (see Table 3-73).

Table 3-72: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Industrial	1,441.9	1,451.7	1,273.5	1,308.9	1,339.4	1,312.0	1,325.0
Residential	580.0	430.0	440.0	450.0	420.0	580.0	580.0
Commercial	65.7	70.0	71.6	69.2	60.7	70.2	73.4
Electricity Generation	128.5	185.0	195.6	182.2	190.2	207.4	251.3
Total	2,216.2	2,136.7	1,980.7	2,010.2	2,010.3	2,169.5	2,229.6

Note: Totals may not sum due to independent rounding.

Table 3-73: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2010	2011	2012	2013	2014
Transportation	60.4	327.4	1,041.4	1,045.0	1,044.6	1,071.6	1,092.8
Industrial	0.8	6.8	16.6	16.7	16.7	17.6	14.4
Commercial	0.5	0.9	3.3	2.9	2.6	2.7	4.1
Total	61.7	335.1	1,061.2	1,064.6	1,063.8	1,091.8	1,111.3

Note: Totals may not sum due to independent rounding.

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. 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 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Wood consumption values for 2013 were revised relative to the previous Inventory based on updated information from EIA's *Monthly Energy Review* (EIA 2016). These revisions of historical data for wood biomass consumption resulted in an average annual increase in emissions from wood biomass consumption of 0.1 MMT CO₂ Eq. (less than 0.1 percent) from 1990 through 2013. Ethanol consumption values remained constant relative to the previous Inventory throughout the entire time-series.

Planned Improvements

The availability of facility-level combustion emissions through EPA's Greenhouse Gas Reporting Program (GHGRP) will be examined to help better characterize the industrial sector's energy consumption in the United States, and further classify 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 the GHGRP may also include industrial process emissions.⁸⁶ 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 CO₂ 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 CO₂ 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 GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.⁸⁷

⁸⁶ See <<http://unfccc.int/resource/docs/2006/sbsta/eng/09.pdf>>.

⁸⁷ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

4. Industrial Processes and Product Use

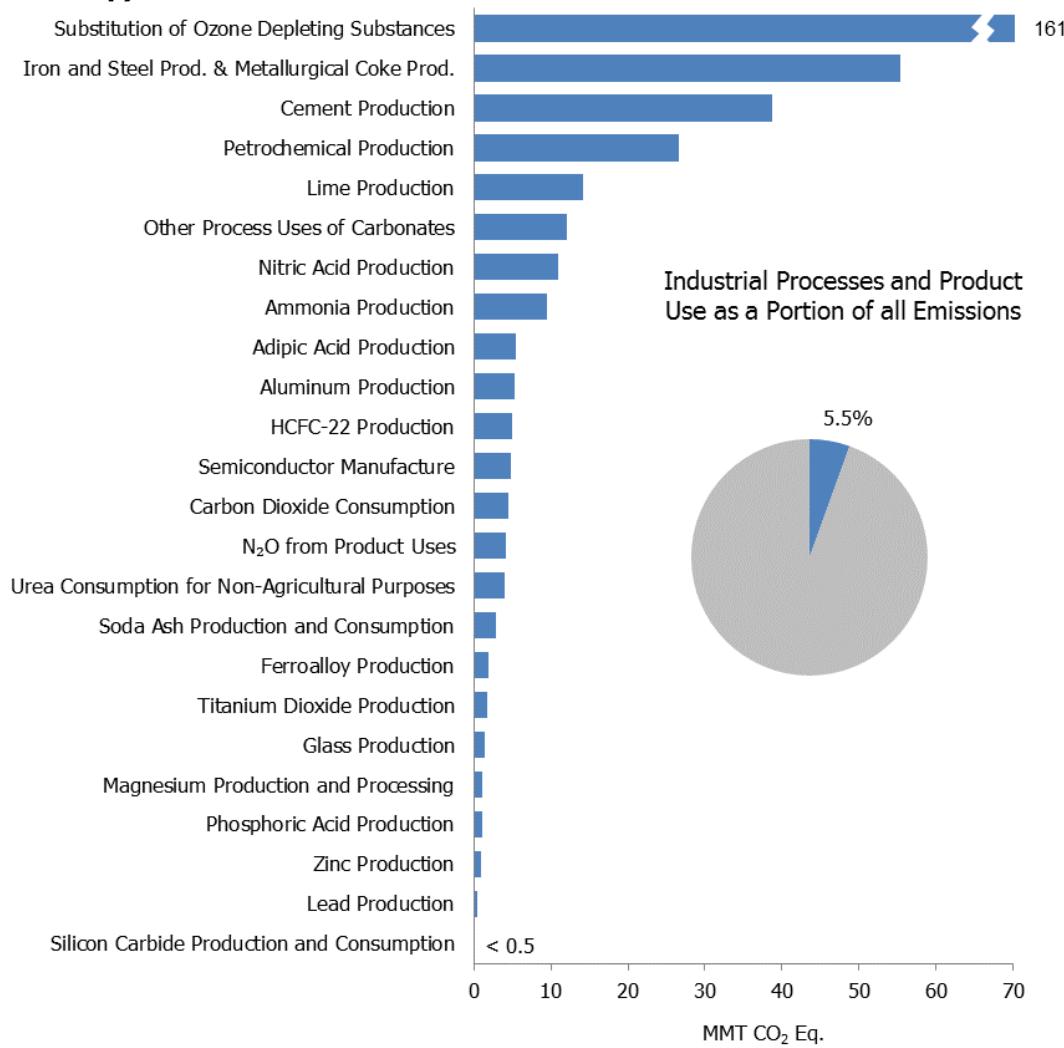
The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1.

Greenhouse gas emissions are produced as the byproducts of various non-energy-related industrial activities. That is, these emissions are produced either from 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), and nitrous oxide (N_2O). The processes included in this chapter include iron and steel production and metallurgical coke production, cement production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and glass manufacturing), ammonia production and urea consumption, petrochemical production, aluminum production, soda ash production and use, titanium dioxide production, CO_2 consumption, ferroalloy production, glass production, zinc production, phosphoric acid production, lead production, silicon carbide production and consumption, nitric acid production, and adipic acid production.

In addition, greenhouse gases are often used in products or by end-consumers. These gases include industrial sources of man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and N_2O . 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 accumulate in the atmosphere as long as emissions continue. 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 (ODSs), 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 aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing. Nitrous oxide is emitted by the production of adipic acid and nitric acid, semiconductor manufacturing, end-consumers in product uses through the administration of anesthetics, and by industry as a propellant in aerosol products.

In 2014, IPPU generated emissions of 379.2 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 5.5 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 178.1 MMT CO_2 Eq. (178,150 kt CO_2) in 2014, or 3.2 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.2 MMT CO_2 Eq. (6 kt CH_4) in 2014, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 20.8 MMT CO_2 Eq. (70 kt N_2O) in 2014, or 5.2 percent of total U.S. N_2O emissions. In 2014 combined emissions of HFCs, PFCs, SF_6 , and NF_3 totaled 180.1 MMT CO_2 Eq. Total emissions from IPPU in 2014 were 11.2 percent more than 1990 emissions. Indirect greenhouse gas emissions also result from IPPU, and are presented in Table 4-107 in kilotons (kt).

Figure 4-1: 2014 Industrial Processes and Product Use Chapter Greenhouse Gas Sources (MMT CO₂ Eq.)



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources. 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). Emissions from mineral sources have either increased or not changed significantly since 1990 but largely track economic cycles, while CO₂ and CH₄ emissions from chemical sources have either decreased or not changed significantly. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990, while the emission trends of HFCs, PFCs, SF₆, and NF₃ from other sources are mixed. Nitrous oxide emissions from the production of adipic and nitric acid have decreased, while N₂O emissions from product uses has remained nearly constant over time. Trends are explained further within each emission source category throughout the chapter.

Table 4-1 summarizes emissions for the IPPU chapter in MMT CO₂ Eq. using *IPCC Fourth Assessment Report* (AR4) GWP values, following the requirements of the revised United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).¹ 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

¹ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

reported to the UNFCCC in the common reporting format tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, SF₆, and NF₃.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	207.1	190.3	168.8	172.9	169.5	171.7	178.1
Iron and Steel Production & Metallurgical Coke Production	99.7	66.5	55.7	59.9	54.2	52.2	55.4
<i>Iron and Steel Production</i>	<i>97.2</i>	<i>64.5</i>	<i>53.6</i>	<i>58.5</i>	<i>53.7</i>	<i>50.4</i>	<i>53.4</i>
<i>Metallurgical Coke Production</i>	<i>2.5</i>	<i>2.0</i>	<i>2.1</i>	<i>1.4</i>	<i>0.5</i>	<i>1.8</i>	<i>1.9</i>
Cement Production	33.3	45.9	31.3	32.0	35.1	36.1	38.8
Petrochemical Production	21.6	27.4	27.2	26.3	26.5	26.4	26.5
Lime Production	11.7	14.6	13.4	14.0	13.7	14.0	14.1
Other Process Uses of Carbonates	4.9	6.3	9.6	9.3	8.0	10.4	12.1
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Carbon Dioxide Consumption	1.5	1.4	4.4	4.1	4.0	4.2	4.5
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Aluminum Production	6.8	4.1	2.7	3.3	3.4	3.3	2.8
Soda Ash Production and Consumption	2.8	3.0	2.7	2.7	2.8	2.8	2.8
Ferroalloy Production	2.2	1.4	1.7	1.7	1.9	1.8	1.9
Titanium Dioxide Production	1.2	1.8	1.8	1.7	1.5	1.7	1.8
Glass Production	1.5	1.9	1.5	1.3	1.2	1.3	1.3
Phosphoric Acid Production	1.5	1.3	1.1	1.2	1.1	1.1	1.1
Zinc Production	0.6	1.0	1.2	1.3	1.5	1.4	1.0
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Silicon 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	0.1	0.1	0.1	0.1	0.2
Petrochemical Production	0.2	0.1	+	+	0.1	0.1	0.1
Ferroalloy Production	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
<i>Iron and Steel Production</i>	<i>+</i>						
<i>Metallurgical Coke Production</i>	<i>0.0</i>						
N₂O	31.6	22.8	20.1	25.5	20.4	19.1	20.8
Nitric Acid Production	12.1	11.3	11.5	10.9	10.5	10.7	10.9
Adipic Acid Production	15.2	7.1	4.2	10.2	5.5	4.0	5.4
N ₂ O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Semiconductor Manufacturing	+	0.1	0.1	0.2	0.2	0.2	0.2
HFCs	46.6	119.9	149.4	154.3	155.9	158.9	166.7
Substitution of Ozone Depleting Substances ^a	0.3	99.7	141.2	145.3	150.2	154.6	161.2
HCFC-22 Production	46.1	20.0	8.0	8.8	5.5	4.1	5.0
Semiconductor Manufacture	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Magnesium Production and Processing	0.0	0.0	+	+	+	0.1	0.1
PFCs	24.3	6.7	4.5	7.0	6.0	5.8	5.6
Semiconductor Manufacture	2.8	3.2	2.7	3.5	3.1	2.9	3.0
Aluminum Production	21.5	3.4	1.9	3.5	2.9	3.0	2.5
SF₆	31.1	14.0	9.5	10.0	7.6	7.2	7.3

Electrical Transmission and Distribution	25.4	10.6	7.0	6.8	5.6	5.4	5.6
Magnesium Production and Processing	5.2	2.7	2.1	2.8	1.6	1.5	1.0
Semiconductor Manufacture	0.5	0.7	0.4	0.4	0.4	0.4	0.7
NF₃	+	0.5	0.6	0.7	0.6	0.6	0.5
Semiconductor Manufacture	+	0.5	0.6	0.7	0.6	0.6	0.5
Total	340.9	354.3	353.0	370.5	360.1	363.5	379.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CO₂	207,054	190,273	168,781	172,898	169,472	171,714	178,150
Iron and Steel Production & Metallurgical Coke Production	99,669	66,543	55,671	59,928	54,229	52,201	55,355
<i>Iron and Steel Production</i>	<i>97,166</i>	<i>64,499</i>	<i>53,586</i>	<i>58,501</i>	<i>53,686</i>	<i>50,378</i>	<i>53,417</i>
<i>Metallurgical Coke Production</i>	<i>2,503</i>	<i>2,044</i>	<i>2,085</i>	<i>1,426</i>	<i>543</i>	<i>1,824</i>	<i>1,938</i>
Cement Production	33,278	45,910	31,256	32,010	35,051	36,146	38,755
Petrochemical Production	21,609	27,380	27,246	26,326	26,464	26,437	26,509
Lime Production	11,700	14,552	13,381	13,981	13,715	14,045	14,125
Other Process Uses of Carbonates	4,907	6,339	9,560	9,335	8,022	10,414	12,077
Ammonia Production	13,047	9,196	9,188	9,292	9,377	9,962	9,436
Carbon Dioxide Consumption	1,472	1,375	4,425	4,083	4,019	4,188	4,471
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	4,730	4,029	4,449	4,179	4,007
Aluminum Production	6,831	4,142	2,722	3,292	3,439	3,255	2,833
Soda Ash Production and Consumption	2,822	2,960	2,697	2,712	2,763	2,804	2,827
Ferroalloy Production	2,152	1,392	1,663	1,735	1,903	1,785	1,914
Titanium Dioxide Production	1,195	1,755	1,769	1,729	1,528	1,715	1,755
Glass Production	1,535	1,928	1,481	1,299	1,248	1,317	1,341
Phosphoric Acid Production	1,529	1,342	1,087	1,151	1,093	1,119	1,095
Zinc Production	632	1,030	1,182	1,286	1,486	1,429	956
Lead Production	516	553	542	538	527	546	518
Silicon Carbide Production and Consumption	375	219	181	170	158	169	173
Magnesium Production and Processing	1	3	1	3	2	2	2
CH₄	12	4	3	3	4	4	6
Petrochemical Production	9	3	2	2	3	3	5
Ferroalloy Production	1	+	+	+	1	+	1
Silicon Carbide Production and Consumption	1	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
<i>Iron and Steel Production</i>	<i>1</i>	<i>1</i>	<i>+</i>	<i>+</i>	<i>+</i>	<i>+</i>	<i>+</i>
<i>Metallurgical Coke Production</i>	<i>0</i>						
N₂O	106	76	68	86	69	64	70
Nitric Acid Production	41	38	39	37	35	36	37
Adipic Acid Production	51	24	14	34	19	13	18
N ₂ O from Product Uses	14	14	14	14	14	14	14
Semiconductor Manufacturing	+	+	+	1	1	1	1
HFCs	M						

Substitution of Ozone Depleting Substances ^a	M	M	M	M	M	M	M	M
HCFC-22 Production	3	1	1	1	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+	+
Magnesium Production and Processing	0	0	+	+	+	+	+	+
PFCs	M							
Semiconductor Manufacture	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M
SF₆	1	1	+	+	+	+	+	+
Electrical Transmission and Distribution	1	+	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+	+
NF₃	+	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

M (Mixture of gases)

^a Small amounts of PFC emissions also result from this source.

Note: Totals may not sum due to independent rounding.

The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines.

QA/QC and Verification Procedures

For industrial processes and product use sources, a detailed QA/QC plan was developed and implemented. This plan was based on the overall The Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory (QA/QC Management Plan), but was tailored to include specific procedures recommended for these sources. Two types of checks were performed using this plan: (1) general, or Tier 1, procedures 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, or Tier 2, procedures that focus on checks 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; that, where possible, consistent and reputable data sources are used across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets and factors are used where applicable. Tier 1 quality assurance and quality control procedures have been performed for all industrial process and product use sources. Tier 2 procedures were performed for more significant emission categories, consistent with the *IPCC Good Practice Guidelines*.

For most industrial process and product use categories, activity data is obtained through a survey of manufacturers conducted by various organizations (specified within each source); the uncertainty of the activity data is a function of the reliability of reported plant-level production data and is influenced by the completeness of the survey response. The emission factors used are defaults from IPCC, derived using calculations that assume precise and efficient chemical reactions, or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically-derived emission factors that are biased; therefore, they may not represent U.S. national averages. Additional assumptions are described within each source.

The uncertainty analysis performed to quantify uncertainties associated with the 2014 emission estimates from industrial processes and product use continues a multi-year process for developing credible quantitative uncertainty estimates for these source categories using the IPCC Tier 2 approach. As the process continues, the type and the

characteristics of the actual probability density functions underlying the input variables are identified and better characterized (resulting in development of more reliable inputs for the model, including accurate characterization of correlation between variables), based primarily on expert judgment. Accordingly, the quantitative uncertainty estimates reported in this section should be considered illustrative and as iterations of ongoing efforts to produce accurate uncertainty estimates. The correlation among data used for estimating emissions for different sources can influence the uncertainty analysis of each individual source. While the uncertainty analysis recognizes very significant connections among sources, a more comprehensive approach that accounts for all linkages will be identified as the uncertainty analysis moves forward.

Box 4-1: Industrial Processes Data from EPA's Greenhouse Gas Reporting Program

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 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). The rule applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO₂ 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 CO₂ Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were reported for facilities subject to 40 CFR part 98, though some source categories first reported data for calendar year 2011.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary. EPA presents the data collected by EPA's GHGRP through a data publication tool (ghgdata.epa.gov) that allows data to be viewed in several formats, including maps, tables, charts, and graphs for individual facilities or groups of facilities. 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. This may differ from the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories 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 report is a comprehensive accounting of all emissions from source categories identified in the IPCC (2006) guidelines. Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.

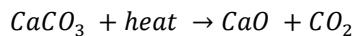
For certain source categories in this Inventory (e.g., nitric acid production and petrochemical production), EPA has also integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is publishing only data values that meet these aggregation criteria.² Specific uses of aggregated facility-level data are described in the respective methodological sections. For other source categories in this chapter, as indicated in the respective planned improvements sections, EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this Inventory, giving particular consideration to ensuring time series consistency and completeness.

² 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>>.

4.1 Cement Production (IPCC Source Category 2A1)

Cement 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 the cement and the chemical process itself. Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter.

During the cement production process, calcium carbonate (CaCO_3) is heated in a cement kiln at a temperature of about 1,450 degrees Celsius (2,700 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 cement production is directly proportional to the lime content of the clinker. During calcination, each mole of limestone (CaCO_3) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2 :



Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier byproduct CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum and potentially other materials (e.g., slag, etc.), and used to make Portland cement.³

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, and Michigan were the five leading cement-producing states in 2014 and accounted for approximately 53 percent of total U.S. production (USGS 2015b). Clinker production in 2014 increased approximately 7 percent from 2013 levels. This increase can be attributed to an increase in spending in new residential construction and nonresidential buildings. In 2014, U.S. clinker production totaled 74,946 kilotons (USGS 2015a). The resulting CO_2 emissions were estimated to be 38.8 MMT CO_2 Eq. (38,755 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	33.3	33,278
2005	45.9	45,910
2010	31.3	31,256
2011	32.0	32,010
2012	35.1	35,051
2013	36.1	36,146
2014	38.8	38,755

Greenhouse gas emissions from cement production increased every year from 1991 through 2006 (with the exception of a slight decrease in 1997), but decreased in the following years until 2009. 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). Since 2010, emissions have increased slightly. In 2014, emissions from cement production increased by 7 percent from 2013 levels.

Emissions since 1990 have increased by 16 percent. Emissions decreased significantly between 2008 and 2009, due to the economic recession and associated decrease in demand for construction materials. Emissions increased

³ Approximately three percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime, etc.) and Portland cement (USGS 2011). Carbon dioxide emissions that result from the production of lime used to create masonry cement are included in the Lime Manufacture source category.

slightly from 2009 levels in 2010, and continued to gradually increase during the 2011 through 2014 time period due to increasing consumption. 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 were estimated using the Tier 2 methodology from the *2006 IPCC Guidelines*. 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, 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 CO₂ 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 0.51 tons of CO₂ per ton of clinker produced, which was determined as follows:

$$EF_{\text{clinker}} = 0.6460 \text{ CaO} \times [(44.01 \text{ g/mole CO}_2 \div (56.08 \text{ g/mole CaO})] = 0.5070 \text{ tons CO}_2/\text{ton clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO₂ emissions should be estimated as two percent of the CO₂ emissions calculated from clinker production (when data on CKD generation are not available). Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2006).

Furthermore, 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 2013b). Clinker production data for 2013 and 2014 were also obtained from USGS (USGS 2015a). The data were compiled by USGS (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including the facilities in Puerto Rico.

Table 4-4: Clinker Production (kt)

Year	Clinker
1990	64,355
2005	88,783
2010	60,444
2011	61,903
2012	67,784
2013	69,901
2014	74,946

Notes: Clinker production from 1990 through 2014 includes Puerto Rico. Data were obtained from USGS (Van Oss 2013a; USGS 2014), whose original data source was USGS and U.S. Bureau of Mines Minerals Yearbooks (2013 data obtained from mineral industry surveys for cement in June 2014; 2014 data obtained from mineral industry surveys for cement in June 2015).

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 CaCO₃, 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). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO₂ 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 CO₂ in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO₂ 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 CO₂ emission factor for clinker production, and the emission factor for additional CO₂ emissions from CKD, 2014 CO₂ emissions from cement production were estimated to be between 36.5 and 41.1 MMT CO₂ 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 38.8 MMT CO₂ Eq.

Table 4-5: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Cement Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	38.8	36.5	41.1	-6%	+6%

^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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

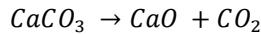
Planned Improvements

Future improvements involve 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. 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 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.⁴ Most facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS), thus reporting combined process and combustion emissions from kilns. EPA's continued assessment will also focus on feasibility to disaggregate aggregated GHGRP emissions consistent with IPCC and UNFCCC guidelines to present both national process and combustion emissions streams.

⁴ See <http://www.ipcc-nngip.iges.or.jp/meeting/pdfs/1008_Model_and_Facility_Level_Report.pdf>.

4.2 Lime Production (IPCC 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.



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.⁵ Emissions from fuels consumed for energy purposes during the production of lime are accounted for 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 ($[\text{CaO}\cdot\text{MgO}]$); and dolomitic hydrate ($[\text{Ca(OH)}_2\cdot\text{MgO}]$ or $[\text{Ca(OH)}_2\cdot\text{Mg(OH)}_2]$).

The current lime market is approximately distributed across five end-use categories as follows: metallurgical uses, 38 percent; environmental uses, 31 percent; chemical and industrial uses, 22 percent; construction uses, 8 percent; and refractory dolomite, 1 percent. The major uses are in steel making, flue gas desulfurization systems at coal-fired electric power plants, construction, and water purification. 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.

Lime production in the United States—including Puerto Rico—was reported to be 19,399 kilotons in 2014 (Corathers 2015). Principal lime producing states are Missouri, Alabama, Kentucky, Ohio, Texas (USGS 2014), Nevada, and Pennsylvania.

U.S. lime production resulted in estimated net CO_2 emissions of 14.1 MMT CO_2 Eq. (14,125 kt) (see Table 4-6 and Table 4-7). The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described below.

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
2010	13.4	13,381
2011	14.0	13,981
2012	13.7	13,715
2013	14.0	14,045
2014	14.1	14,125

⁵ 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.

Table 4-7: Potential, Recovered, and Net CO₂ Emissions from Lime Production (kt)

Year	Potential	Recovered^a	Net Emissions
1990	11,959	259	11,700
2005	15,074	522	14,552
2010	13,776	395	13,381
2011	14,389	407	13,981
2012	14,188	473	13,715
2013	14,513	467	14,045
2014	14,630	505	14,125

^a For sugar refining and PCC production.

Note: Totals may not sum due to independent rounding.

In 2014, lime production was nearly the same as 2013 levels (increase of 1 percent) at 19,399 kilotonnes.

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* (IPCC 2006). The emission factor is the product of the stoichiometric ratio between CO₂ 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 H₂O to (Ca(OH)₂) and [Ca(OH)₂•Mg(OH)₂] (IPCC 2006). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.2 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. 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).

Lime emission estimates were further adjusted to account for the amount of CO₂ 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 CO₂ captured for on-site process use was obtained from EPA's GHGRP (EPA 2015) based on reported facility level data for years 2010 through 2014. The amount of CO₂ captured/recovered for on-site process use is deducted from the total potential 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 CO₂ removals (i.e., CO₂ captured/recovered) was available only for 2010 through 2014. 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 (*2006 IPCC Guidelines*, Volume 1, Chapter 5). The prior estimates for CO₂ removal for 1990 through 2009 were adjusted based on the "overlap" technique recommended by IPCC. Refer to the Recalculations Discussion section, below, for more details.

Lime production data (by type, high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2014 (see Table 4-8) were obtained from the U.S. Geological Survey

(USGS) (1992 through 2014; Corathers 2015) and are compiled by USGS to the nearest ton. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2011). 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 is presented in Table 4-9 (IPCC 2006). The CaO and CaO•MgO contents of lime 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
2010	13,300	2,570	1,910	239	200
2011	13,900	2,690	2,010	230	200
2012	13,600	2,710	2,020	237	200
2013	13,800	2,870	2,050	260	200
2014	14,000	2,730	2,190	279	200

Table 4-9: Adjusted Lime Production (kt)

Year	High-Calcium	Dolomitic
1990	12,466	2,800
2005	15,721	3,522
2010	14,694	2,937
2011	15,367	3,051
2012	15,075	3,076
2013	15,297	3,252
2014	15,599	3,125

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 CO₂ 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 CO₂ 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, CO₂ 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 CO₂; whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO₂ 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 CO₂ are “reused” are required to quantify the amount of CO₂ that is reabsorbed. Research conducted thus far has not

yielded the necessary information to quantify CO₂ reabsorption rates.⁶ However, some additional information on the amount of CO₂ consumed on site at lime facilities has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.⁷ 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 CO₂—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO₂ 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). There is limited data publicly available on LKD generation rates and also quantities, types of other byproducts/wastes produced at lime facilities. Further research and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on IPCC guidelines. In preparing estimates for the current inventory, EPA initiated a dialogue with NLA to discuss data needs to generate a country specific LKD factor and is reviewing the information provided by NLA.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO₂ emissions for 2014 were estimated to be between 13.8 and 14.5 MMT CO₂ Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 3 percent below and 3 percent above the emission estimate of 14.1 MMT CO₂ Eq.

Table 4-10: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Lime Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	14.1	13.8	14.5	-3%	+3%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

⁶ Representatives of the National Lime Association estimate that CO₂ reabsorption that occurs from the use of lime may offset as much as a quarter of the CO₂ emissions from calcination (Males 2003).

⁷ Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO₂. 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) [CaC₂ + 2H₂O → C₂H₂ + Ca(OH)₂], not calcium carbonate [CaCO₃]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [Ca(OH)₂ + heat → CaO + H₂O] and no CO₂ is released.

Recalculations Discussion

Dead-burned dolomite production data for 2013 were updated relative to the previous Inventory based on the more recent *Minerals Yearbook: Lime 2013 [Advanced Release]* (USGS 2014). This caused a slight decrease in 2013 emissions, by approximately 0.2 percent.

Planned Improvements

Future improvements involve evaluating recently obtained data to improve 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. In response to comments, EPA met with NLA on April 7, 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 response to this technical meeting, in January and February 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives over 2002 through 2011 associated with generation of total calcined byproducts and LKD (LKD reporting only differentiated starting in 2010). This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol also recently provided.

4.3 Glass Production (IPCC Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of CO₂ from both the energy consumed in making glass and the glass process itself. Emissions from fuels consumed for energy purposes during the production of glass are accounted for 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) which emit process-related carbon dioxide (CO₂) emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO₂). 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, Na₂CO₃) and potash (potassium carbonate, K₂O). 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 are limestone (CaCO₃), dolomite (CaCO₃MgCO₃), alumina (Al₂O₃), magnesia (MgO), barium carbonate (BaCO₃), strontium carbonate (SrCO₃), lithium carbonate (Li₂CO₃), and zirconia (ZrO₂) (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 cullet broker services.

The raw materials (primarily limestone, dolomite and soda ash) release CO₂ 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 CO₂ 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 over 1,500 companies that manufacture glass in the United States, with the largest being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.⁸

⁸ 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>>.

In 2014, 775 kilotons of limestone and 2,410 kilotons of soda ash were consumed for glass production (USGS 2015a; Willett 2015). Dolomite consumption data for glass manufacturing was reported to be zero for 2014. Use of limestone and soda ash in glass production resulted in aggregate CO₂ emissions of 1.3 MMT CO₂ Eq. (1,341 kt) (see Table 4-11). Overall, emissions have decreased 13 percent from 1990 through 2014.

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 a corresponding decrease in 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 2014).

Table 4-11: CO₂ Emissions from Glass Production (MMT CO₂ Eq. and kt)

Year	MMT CO ₂ Eq.	kt
1990	1.5	1,535
2005	1.9	1,928
2010	1.5	1,481
2011	1.3	1,299
2012	1.2	1,248
2013	1.3	1,317
2014	1.3	1,341

Note: Totals may not sum due to independent rounding

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 CO₂/metric ton carbonate): limestone, 0.43971; dolomite, 0.47732; and soda ash, 0.41492.

Consumption data for 1990 through 2014 of limestone, dolomite, and soda ash used for glass manufacturing were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995 through 2015b), 2014 preliminary data from the USGS Crushed Stone Commodity Expert (Willett 2015), the *USGS Minerals Yearbook: Soda Ash Annual Report* (1995 through 2014), USGS Mineral Industry Surveys for Soda Ash in January 2015 (USGS 2015a) and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

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; or (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years.

There is a large quantity of limestone and dolomite reported to the USGS under the categories “unspecified-reported” and “unspecified–estimated.” A portion of this consumption is believed to be limestone or dolomite used for glass manufacturing. The quantities listed under the “unspecified” categories were, therefore, allocated to glass

manufacturing according to the percent limestone or dolomite consumption for glass manufacturing end use for that year.⁹

Based on the 2014 reported data, the estimated distribution of soda ash consumption for glass production compared to total domestic soda ash consumption is 48 percent (USGS 2015a).

Table 4-12: Limestone, Dolomite, and Soda Ash Consumption Used in Glass Production (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Limestone	430	920	999	614	555	693	775
Dolomite	59	541	0	0	0	0	0
Soda Ash	3,177	3,050	2,510	2,480	2,420	2,440	2,410
Total	3,666	4,511	3,509	3,094	2,975	3,133	3,185

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 & soda ash) and not the end user. For 2014, there has been no reported consumption of dolomite for glass manufacturing. This data has 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 2014, glass production CO₂ emissions were estimated to be between 1.3 and 1.4 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below and 5 percent above the emission estimate of 1.3 MMT CO₂ Eq.

Table 4-13: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Glass Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	1.3	1.4	-4%	+5%

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

⁹ This approach was recommended by USGS.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Limestone and dolomite consumption data for 2013 were revised to reflect updated USGS data (USGS 2015b). This change resulted in an increase of CO₂ emissions by approximately 14 percent. The preliminary data for 2013 was obtained directly from the USGS Crushed Stone Commodity Expert (Willett 2014). In April 2015, USGS published the *2013 Minerals Yearbook* for Crushed Stone and the preliminary data were revised to reflect the latest USGS published data. The published time series was reviewed to ensure time series consistency. Details on the emission trends through time are described in more detail in the Methodology section above.

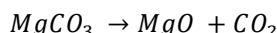
Planned Improvements

Currently, only limestone and soda ash consumption data for glass manufacturing is publicly available. While limestone and soda ash are the predominant carbonates used in glass manufacturing, there are other carbonates that are also consumed for glass manufacturing, although in smaller quantities. Pending resources, future improvements will include research into other sources of data for carbonate consumption by the glass industry, including EPA's Greenhouse Gas Reporting Program (GHGRP).

Additionally, future improvements will also include finalizing assessment and integration of data reported under EPA's GHGRP to improve the emission estimates and completeness for the Glass Production source category. 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 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 addition, EPA's GHGRP has an emission threshold for reporting, so the data do not account for all glass production in the United States. 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.¹⁰

4.4 Other Process Uses of Carbonates (IPCC Source Category 2A4)

Limestone (CaCO₃), dolomite (CaCO₃MgCO₃),¹¹ 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 and dolomite use. For industrial applications, carbonates such as limestone and dolomite are heated sufficiently enough to calcine the material and generate CO₂ as a byproduct.



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 this section and reported under their respective source

¹⁰ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Data_Report.pdf>.

¹¹ Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

categories (e.g., Section 4.3, Glass Production (IPCC Source Category 2A3)). Emission from soda ash consumption is reported under respective categories (e.g., Glass Manufacturing (IPCC Source Category 2A3) and Soda Ash Production and Consumption (IPCC Source Category 2B7)). Emissions from fuels consumed for energy purposes during these processes are accounted for in the Energy chapter.

Limestone is 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. The leading limestone producing states are Texas, Missouri, Florida, Ohio, and Pennsylvania, which contribute 43 percent of the total U.S. output (USGS 2015). Similarly, dolomite deposits are also widespread throughout the world. Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Illinois, Pennsylvania, and New York, which contribute 55 percent of the total U.S. output (USGS 2015).

In 2014, 25,085 kt of limestone and 3,359 kt of dolomite were consumed for these emissive applications, excluding glass manufacturing (Willett 2015). Usage of limestone and dolomite resulted in aggregate CO₂ emissions of 12.1 MMT CO₂ Eq. (12,077 kt) (see Table 4-14 and Table 4-15). Overall, emissions have increased 146 percent from 1990 through 2014.

Table 4-14: CO₂ Emissions from Other Process Uses of Carbonates (MMT CO₂ Eq.)

Year	Flux Stone	FGD	Magnesium Production	Other Miscellaneous Uses ^a	Total
1990	2.6	1.4	0.1	0.8	4.9
2005	2.6	3.0	0.0	0.7	6.3
2010	1.6	7.1	0.0	0.9	9.6
2011	1.5	5.4	0.0	2.4	9.3
2012	1.1	5.8	0.0	1.1	8.0
2013	2.3	6.3	0.0	1.8	10.4
2014	2.9	7.2	0.0	1.9	12.1

^a “Other miscellaneous uses” include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Note: Totals may not sum due to independent rounding.

Table 4-15: CO₂ Emissions from Other Process Uses of Carbonates (kt)

Year	Flux Stone	FGD	Magnesium Production	Other Miscellaneous Uses ^a	Total
1990	2,592	1,432	64	819	4,907
2005	2,649	2,973	0	718	6,339
2010	1,560	7,064	0	937	9,560
2011	1,467	5,420	0	2,449	9,335
2012	1,077	5,797	0	1,148	8,022
2013	2,307	6,309	0	1,798	10,414
2014	2,932	7,212	0	1,933	12,077

^a “Other miscellaneous uses” include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Note: Totals may not sum due to independent rounding.

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, Table 2.1—limestone: 0.43971 metric ton CO₂/metric ton carbonate, and dolomite: 0.47732 metric ton CO₂/metric ton carbonate.¹² 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 CO₂ 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 CO₂ emissions ceased its operations (USGS 1995b through 2012; USGS 2013a).

Consumption data for 1990 through 2014 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 2015), preliminary data for 2014 from USGS Crushed Stone Commodity Expert (Willett 2015), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. The production capacity data for 1990 through 2014 of dolomitic magnesium metal also came from the USGS (1995b through 2012; USGS 2013a) 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. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

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 each reported end-use according to each end-use’s fraction of total consumption in that year.¹³

Table 4-16: Limestone and Dolomite Consumption (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Flux Stone	6,737	7,022	4,440	4,396	3,666	6,345	7,648
Limestone	5,804	3,165	1,921	2,531	3,108	4,380	4,304
Dolomite	933	3,857	2,520	1,865	559	1,965	3,344
FGD	3,258	6,761	16,064	12,326	13,185	14,347	16,402
Other Miscellaneous Uses	1,835	1,632	2,121	5,548	2,610	3,973	4,395
Total	11,830	15,415	22,626	22,270	19,461	24,665	28,444

Note: Totals may not sum due to independent rounding.

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

¹² 2006 IPCC Guidelines, Volume 3: Chapter 2.

¹³ 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/industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, 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.

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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-17. Carbon dioxide emissions from other process uses of carbonates in 2014 were estimated to be between 10.7 and 14.0 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 15 percent above the emission estimate of 12.1 MMT CO₂ Eq.

Table 4-17: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Other Process Uses of Carbonates (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	12.1	10.7	14.0	-12%	+15%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Limestone and dolomite consumption data, by end-use, for 2013 were updated relative to the previous Inventory based on the recently published *2013 Minerals Yearbook: Crushed Stone*. In the previous Inventory report (i.e., 1990 through 2013), preliminary data were used for 2013 and updated for the current Inventory. In April 2015, USGS published the *2013 Minerals Yearbook for Crushed Stone* and the preliminary data were revised to reflect the latest USGS published data. The published time series was reviewed to ensure time series consistency. This update caused an increase in total limestone and dolomite consumption for emissive end uses in 2013 by approximately 120 percent. The revised 2013 emission estimate increased by approximately 135 percent relative to the previous report due to this change.

Planned Improvements

In future Inventory reports, this section will integrate and present emissions from soda ash consumption for other chemical uses (non-glass production). Currently, in this document, these estimates are presented along with emissions from soda ash production (IPCC Category 2B7).

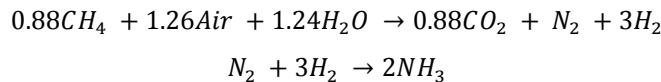
4.5 Ammonia Production (IPCC Source Category 2B1)

Emissions of carbon dioxide (CO₂) occur during the production of synthetic ammonia, primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO₂ and hydrogen (H₂), 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 CO₂ emissions. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter.

In the United States, the majority of ammonia is produced using a natural gas feedstock; however one synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO₂ produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. There are approximately 13 companies operating 26 ammonia producing facilities in 17 states. More than 56 percent of domestic ammonia production capacity is concentrated in the states of Louisiana (29 percent), Oklahoma (21 percent), and Texas (6 percent) (USGS 2015).

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts methane (CH₄) to CO₂, carbon monoxide (CO), and H₂ in the presence of a catalyst. Only 30 to 40 percent of the CH₄ feedstock to the primary reformer is converted to CO and CO₂ in this step of the process. The secondary reforming step converts the remaining CH₄ feedstock to CO and CO₂. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO₂ 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 hydrogen gas is combined with the nitrogen (N₂) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO₂ is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO₂ is released from the solution.

The conversion process for conventional steam reforming of CH₄, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:



To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO₂ and H₂. These gases are separated, and the H₂ is used as a feedstock to the ammonia production process, where it is reacted with N₂ to form ammonia.

Not all of the CO₂ produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO₂ produced by the synthetic ammonia process are used as raw materials in the production of urea [CO(NH₂)₂], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:



Only the CO₂ emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO₂ that is captured during the ammonia production process and used to produce urea does not contribute to the CO₂ emission estimates for ammonia production presented in this section. Instead, CO₂ 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 CO₂ resulting from agricultural applications of urea are accounted for in the *Cropland Remaining Cropland* section of the Land Use, Land-Use Change, and Forestry chapter. Emissions of CO₂ resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in the Urea Consumption for Non-Agricultural Purposes section of this chapter.

Total emissions of CO₂ from ammonia production in 2014 were 9.4 MMT CO₂ Eq. (9,436 kt), and are summarized in Table 4-18 and Table 4-19. 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 28 percent. Emissions in 2014 have decreased by approximately 5 percent from the 2013 levels.

Table 4-18: CO₂ Emissions from Ammonia Production (MMT CO₂ Eq.)

Source	1990	2005	2010	2011	2012	2013	2014
Ammonia Production	13.0	9.2	9.2	9.3	9.4	10.0	9.4
Total	13.0	9.2	9.2	9.3	9.4	10.0	9.4

Table 4-19: CO₂ Emissions from Ammonia Production (kt)

Source	1990	2005	2010	2011	2012	2013	2014
Ammonia Production	13,047	9,196	9,188	9,292	9,377	9,962	9,436
Total	13,047	9,196	9,188	9,292	9,377	9,962	9,436

Methodology

Carbon dioxide emissions from production of synthetic ammonia from natural gas feedstock is based on the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 method. A country-specific emission factor is developed and applied to national ammonia production to estimate emissions. The method uses a CO₂ emission factor published by the European Fertilizer Manufacturers Association (EFMA) that is based on natural gas-based ammonia production technologies that are similar to those employed in the United States. This CO₂ emission factor of 1.2 metric tons CO₂/metric ton NH₃ (EFMA 2000a) is applied to the percent of total annual domestic ammonia production from natural gas feedstock.

Emissions of CO₂ from ammonia production are then adjusted to account for the use of some of the CO₂ produced from ammonia production as a raw material in the production of urea. The CO₂ 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 CO₂/urea factor of 44/60, assuming complete conversion of ammonia (NH₃) and CO₂ 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 4-20. The CO₂ emission factor for production of ammonia from petroleum coke is based on plant-specific data, wherein all carbon contained in the petroleum coke feedstock that is not used for urea production is assumed to be emitted to the atmosphere as CO₂ (Bark 2004). 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. The CO₂ emission factor of 3.57 metric tons CO₂/metric ton NH₃ for the petroleum coke feedstock process (Bark 2004) is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock.

The emission factor of 1.2 metric ton CO₂/metric ton NH₃ for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, Production of Ammonia (EFMA 2000a). The EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO₂/metric ton NH₃, with 1.2 metric ton CO₂/metric ton NH₃ 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 CH₄ feedstock to the catalytic reforming process is ultimately converted to CO₂. As noted earlier, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. The total ammonia production data for 2011, 2012, 2013, and 2014 were obtained from American Chemistry Council (2015). For years before 2011, ammonia production data (see Table 4-20) 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 2010) 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, 2014, and 2015) for 2012, 2013, and 2014. 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, and urea production data for 2011, 2012, and 2013 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2014, 2015). The urea production data for 2014 are not yet published and so 2013 data were used as proxies for 2014.

Table 4-20: Ammonia Production and Urea Production (kt)

Year	Ammonia Production	Urea Production
1990	15,425	7,450
2005	10,143	5,270
2010	10,084	5,122
2011	10,325	5,430
2012	10,305	5,220
2013	10,930	5,480
2014	10,515	5,480

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 collocated plants from the same natural gas raw material.

Recovery of CO₂ from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO₂ emissions from ammonia production, as data concerning the disposition of recovered CO₂ are not available. Such recovery may or may not affect the overall estimate of CO₂ emissions depending upon the end use to which the recovered CO₂ is applied. Further research is required to determine whether byproduct CO₂ is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-21. Carbon dioxide emissions from ammonia production were estimated to be between 8.7 and 10.2 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 9.4 MMT CO₂ Eq.

Table 4-21: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Ammonia Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	9.4	8.7	10.2	-8%	+8%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Production estimates for urea production for 2013 were updated relative to the previous Inventory using information obtained from the recent *2013 Minerals Yearbook: Nitrogen* (USGS 2015). For the previous version of the Inventory (i.e., 1990 through 2013), 2012 data was used as a proxy for 2013 as the 2013 data were not published prior to the previous Inventory report. This update resulted in a slight decrease of emissions by approximately 2 percent for 2013 relative to the previous report.

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 2015, that include necessary activity data. 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.¹⁴ Specifically, the planned improvements include assessing data to update the emission factors to include both fuel and feedstock CO₂ emissions and incorporate CO₂ capture and storage. Methodologies will also be updated if additional ammonia production plants are found to use hydrocarbons other than natural gas for ammonia production.

4.6 Urea Consumption for Non-Agricultural Purposes

Urea is produced using ammonia and carbon dioxide (CO₂) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO₂ are generated. There are approximately 20 of these facilities operating in the United States.

The chemical reaction that produces urea is:



¹⁴ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

This section accounts for CO₂ emissions associated with urea consumed exclusively for non-agricultural purposes. Carbon dioxide emissions associated with urea consumed for fertilizer are accounted for in the *Cropland Remaining Cropland* section of the Land Use, Land-Use Change, and Forestry chapter.

Urea is used as a nitrogenous fertilizer for agricultural applications and also in a variety of industrial applications. 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 CO₂ from urea consumed for non-agricultural purposes in 2014 were estimated to be 4.0 MMT CO₂ Eq. (4,007 kt), and are summarized in Table 4-22 and Table 4-23. 2014 data on urea production data, urea exports and imports are not yet published. 2013 data has been used as proxy for 2014. Net CO₂ emissions from urea consumption for non-agricultural purposes in 2014 have increased by approximately 6 percent from 1990.

Table 4-22: CO₂ Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO₂ Eq.)

Source	1990	2005	2010	2011	2012	2013	2014
Urea Consumption	3.8	3.7	4.7	4.0	4.4	4.2	4.0
Total	3.8	3.7	4.7	4.0	4.4	4.2	4.0

Table 4-23: CO₂ Emissions from Urea Consumption for Non-Agricultural Purposes (kt)

Source	1990	2005	2010	2011	2012	2013	2014
Urea Consumption	3,784	3,653	4,730	4,029	4,449	4,179	4,007
Total	3,784	3,653	4,730	4,029	4,449	4,179	4,007

Methodology

Emissions of CO₂ 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 CO₂ 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 CO₂ during use, and consistent with the *2006 IPCC Guidelines* (IPCC 2006).

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 Land Use, Land-Use Change, and Forestry chapter (see Table 6-30) and is reported in Table 4-24, from the total domestic supply of urea. The domestic supply of urea is estimated based on the amount of urea produced plus the sum of net urea imports and exports. A factor of 0.733 tons of CO₂ per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO₂ emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO₂ per ton of urea emission factor is based on the stoichiometry of producing urea from ammonia and CO₂. This corresponds to a stoichiometric CO₂/urea factor of 44/60, assuming complete conversion of NH₃ and CO₂ to urea (IPCC 2006; EFMA 2000).

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 (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011, therefore, urea production data for 2011, 2012, and 2013 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2014 through 2015). Urea production data for 2014 are not yet publicly available and so 2013 data have been used as proxy.

Urea import data for 2014 are not yet publicly available and so 2013 data have been used as proxy. Urea import data for 2013 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2015). 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). 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 1998 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 4-24). Urea export data for 2014 are not yet publicly available and so 2013 data have been used as proxy. Urea export data for 2013 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 2015). 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).

Table 4-24: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	7,450	3,296	1,860	854
2005	5,270	4,779	5,026	536
2010	5,122	5,152	6,631	152
2011	5,430	5,589	5,860	207
2012	5,220	5,762	6,944	336
2013	5,480	5,921	6,470	330
2014	5,480	6,156	6,470	330

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 CO₂ during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-25. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes were estimated to be between 3.5 and 4.5 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 4.0 MMT CO₂ Eq.

Table 4-25: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	4.0	3.5	4.5	-12%	+12%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

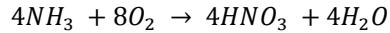
Production estimates for urea production and estimates for urea exports and imports for 2013 were updated using information obtained from the *Minerals Yearbook: Nitrogen* (USGS 2015). Also, the amount of urea consumed for agricultural purposes in the United States for 2013 was revised based on the most recent data obtained from the Land Use, Land-Use Change, and Forestry chapter (see Table 6-30). These updates resulted in a decrease in the emission estimate relative to the previous report of approximately 10 percent in 2013.

4.7 Nitric Acid Production (IPCC 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. It 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 percent or greater nitric acid) can be produced from dehydrating, bleaching, condensing, and absorption of the weak nitric acid. The basic process technology for producing nitric acid has not changed significantly over time. Most U.S. plants were built between 1960 and 2000. As of 2014, there were 34 active weak nitric acid production plants, including one high-strength nitric acid production plant in the United States (EPA 2010; EPA 2015).

During this reaction, 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 accounted for 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:



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 . However, NSCR units 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 with NSCRs installed at 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 10.9 MMT CO₂ Eq. (37 kt of N_2O) in 2014 (see Table 4-26). Emissions from nitric acid production have decreased by 10 percent since 1990, with the trend in the time series closely tracking the changes in production. Emissions have decreased by 24 percent since 1997, the highest year of production in the time series.

Table 4-26: 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
2010	11.5	39
2011	10.9	37

2012	10.5	35
2013	10.7	36
2014	10.9	37

Methodology

Emissions of N₂O were calculated using the estimation methods provided by the *2006 IPCC Guidelines* (IPCC 2006) and country specific methods from EPA's Greenhouse Gas Reporting Program (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 N₂O emissions for 2010 through 2014.

2010 through 2014

Process N₂O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2014 by aggregating reported facility-level data (EPA 2015). In the United States, all nitric acid facilities producing weak nitric acid (30 to 70 percent in strength) are required to report annual greenhouse gas emissions data to EPA as per the requirements of its GHGRP. As of 2014, there were 34 facilities that reported to EPA, including the known single high-strength nitric acid production facility in the United States (EPA 2015). All nitric acid (weak acid) facilities are required to calculate process emissions using a site-specific emission factor developed through annual performance testing under typical operating conditions or by directly measuring N₂O emissions using monitoring equipment. The high-strength nitric acid facility also reports N₂O emissions associated with weak acid production and this may capture all relevant emissions, pending additional further EPA research. More details on the calculation and monitoring methods applicable to Nitric Acid facilities can be found under Subpart V: Nitric Acid Production of the regulation, Part 98.¹⁵

1990 through 2009

Using the GHGRP data for 2010,¹⁶ country-specific N₂O 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 N₂O/metric ton HNO₃ produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.98 kg N₂O/metric ton HNO₃ 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 N₂O emissions from nitric acid production for years prior to the availability of EPA's GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted 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 also year over 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 N₂O abatement technologies are not known at most facilities, but it is assumed that facilities reporting abatement technology use

¹⁵ See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

¹⁶ National N₂O 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 2014 (i.e., percent production with and without abatement).

have had this technology installed and operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N₂O emission factors were used in conjunction with annual production to estimate N₂O emissions for 1990 through 2009, using the following equations:

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = [(\%P_{c,i} \times EF_c) + (\%P_{unc,i} \times EF_{unc})]$$

where,

E _i	= Annual N ₂ O Emissions for year i (kg/yr)
P _i	= Annual nitric acid production for year i (metric tons HNO ₃)
EF _{weighted,i}	= Weighted N ₂ O emission factor for year i (kg N ₂ O/metric ton HNO ₃)
%P _{c,i}	= Percent national production of HNO ₃ with N ₂ O abatement technology (%)
EF _c	= N ₂ O emission factor, with abatement technology (kg N ₂ O/metric ton HNO ₃)
%P _{unc,i}	= Percent national production of HNO ₃ without N ₂ O abatement technology (%)
EF _{unc}	= N ₂ O emission factor, without abatement technology (kg N ₂ O/metric ton HNO ₃)
i	= year from 1990 through 2009

- For 2009: Weighted N₂O emission factor – 5.45 kg N₂O/metric ton HNO₃.
- For 1990 through 2008: Weighted N₂O emission factor – 5.65 kg N₂O/metric ton HNO₃.

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 4-27). 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). Publicly-available data on use of abatement technologies were not available for 1990 through 2007. Therefore, the share of national production with and without abatement for 2008 was assumed to be constant for 1990 through 2007.

Table 4-27: Nitric Acid Production (kt)

Year	kt
1990	7,195
2005	6,711
2010	7,444
2011	7,606
2012	7,453
2013	7,572
2014	7,656

Uncertainty and Time-Series Consistency

Uncertainty associated with the parameters used to estimate N₂O emissions includes that of production data, 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.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-28. Nitrous oxide emissions from nitric acid production were estimated to be between 10.4 and 11.5 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2014 emissions estimate of 10.9 MMT CO₂ Eq.

Table 4-28: Approach 2 Quantitative Uncertainty Estimates for N₂O Emissions from Nitric Acid Production (MMT CO₂ Eq. and Percent)

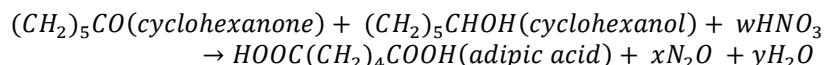
Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N ₂ O	10.9	10.4	11.5	-5%	+5%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.8 Adipic Acid Production (IPCC Source Category 2B3)

Adipic acid is produced through a two-stage process during which nitrous oxide (N₂O) 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:



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 N₂O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). One small plant, which last operated in April 2006 and represented approximately two percent of production, did not control for N₂O (VA DEQ 2009; ICIS 2007; VA DEQ 2006). In 2014, catalytic reduction, non-selective catalytic reduction (NSCR) and thermal reduction abatement technologies were applied as N₂O abatement measures at adipic acid facilities (EPA 2015).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers. In 2014, the United States had two companies with a total of three adipic acid production facilities (two in Texas and one in Florida), all of which were operational (EPA 2015). The United States accounts for the largest share of global adipic acid production capacity (30 percent), followed by the European Union (29 percent) and China (22 percent) (SEI 2010). 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).

Nitrous oxide emissions from adipic acid production were estimated to be 5.4 MMT CO₂ Eq. (18 kt N₂O) in 2014 (see Table 4-29). National adipic acid production has increased by approximately 36 percent over the period of 1990 through 2014, to approximately 1,025,000 metric tons (ACC 2015). Over the period 1990 through 2014, emissions have been reduced by 64 percent due to both the widespread installation of pollution control measures in the late 1990s and plant idling in the late 2000s. In April 2006, the smallest of the four facilities ceased production of adipic acid (VA DEQ 2009); furthermore, one of the major adipic acid production facilities was not operational in

2009 or 2010 (Desai 2010). All three remaining facilities were in operation in 2014. Very little information on annual trends in the activity data exist for adipic acid.

Table 4-29: N₂O Emissions from Adipic Acid Production (MMT CO₂ Eq. and kt N₂O)

Year	MMT CO ₂ Eq.	kt N ₂ O
1990	15.2	51
2005	7.1	24
2010	4.2	14
2011	10.2	34
2012	5.5	19
2013	4.0	13
2014	5.4	18

Methodology

Emissions are estimated using both Tier 2 and Tier 3 methods consistent with the *2006 IPCC Guidelines* (IPCC 2006). Due to confidential business information, plant names are not provided in this section. Therefore, the four adipic acid-producing facilities will be referred to as Plants 1 through 4. Plant 4 was closed in April 2006. Overall, as noted above, the three plants that are currently operating facilities use abatement equipment. Plants 1 and 2 employ catalytic destruction and Plant 3 employs thermal destruction.

2010 through 2014

All emission estimates for 2010 through 2014 were obtained through analysis of EPA's GHGRP data (EPA 2014 through 2015), which is consistent with the *2006 IPCC Guidelines* (IPCC 2006) Tier 3 method. Facility-level greenhouse gas emissions data were obtained from the GHGRP for the years 2010 through 2014 (EPA 2014 through 2015) and aggregated to national N₂O 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 N₂O emissions using monitoring equipment. More information on the monitoring methods for process N₂O emissions applicable to adipic acid production facilities under Subpart E can be found in the electronic code of federal regulations.¹⁷

1990 through 2009

For years prior to EPA's GHGRP reporting, for both Plants 1 and 2, 1990 to 2009 emission estimates were obtained directly from the plant engineer and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered confidential business information and hence are not published (Desai 2010). These estimates were based on continuous process monitoring equipment installed at the two facilities. In 2009 and 2010, no adipic acid production occurred at Plant 1 per reporting to EPA's GHGRP (EPA 2012; Desai 2011b).

For the Plant 4, 1990 through 2009 N₂O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines* until shutdown of the plant in 2006:

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E _{aa}	=	N ₂ O emissions from adipic acid production, metric tons
Q _{aa}	=	Quantity of adipic acid produced, metric tons

¹⁷ See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

EF_{aa}	=	Emission factor, metric ton N_2O /metric ton adipic acid produced
DF	=	N_2O destruction factor
UF	=	Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated, based on experiments that the reaction stoichiometry for N_2O production in the preparation of adipic acid, to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The “ N_2O destruction factor” in the equation represents the percentage of N_2O 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. No abatement equipment was installed at the Inolex/Allied Signal facility, which last operated in April 2006 (VA DEQ 2009). Plant-specific production data for this facility were obtained across the time series from 1990 through 2006 from the Virginia Department of Environmental Quality (VA DEQ 2010). 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 2011a). 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 2015; 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 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 kept the same as the 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 4-30) from 1990 through 2014 were obtained from the American Chemistry Council (ACC 2015).

Table 4-30: Adipic Acid Production (kt)

Year	kt
1990	755
2005	865
2010	720
2011	840
2012	950
2013	980
2014	1,025

Uncertainty and Time-Series Consistency

Uncertainty associated with N_2O 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 4-31. Nitrous oxide emissions from adipic acid production for 2014 were estimated to be between 5.2 and 5.6 MMT CO_2 Eq. at the 95

percent confidence level. These values indicate a range of approximately 4 percent below to 4 percent above the 2014 emission estimate of 5.4 MMT CO₂ Eq.

Table 4-31: Approach 2 Quantitative Uncertainty Estimates for N₂O Emissions from Adipic Acid Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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 ₂ O	5.4	5.2	5.6	-4%	+4%

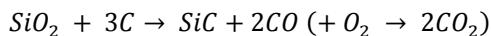
^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.9 Silicon Carbide Production and Consumption (IPCC Source Category 2B5)

Carbon dioxide (CO₂) and methane (CH₄) are emitted from the production of silicon carbide (SiC), a material used as an industrial abrasive. Silicon carbide is produced for abrasive, metallurgical, and other non-abrasive applications in the United States. Production for metallurgical and other non-abrasive applications is not available and therefore both CO₂ and CH₄ estimates are based solely upon production estimates of silicon carbide for abrasive applications. 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 (SiO₂) is reacted with carbon 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 carbon is emitted as CO₂, CH₄, or carbon monoxide (CO). The overall reaction is shown below (but in practice it does not proceed according to stoichiometry):



Carbon dioxide is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications.

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 2006a). 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. However, demand for SiC consumption in the United States has recovered somewhat from its low in 2009 (USGS 2012a). Silicon carbide is manufactured at a single facility located in Illinois (USGS 2015a).

Carbon dioxide emissions from SiC production and consumption in 2014 were 0.2 MMT CO₂ Eq. (173 kt CO₂). Approximately 53 percent of these emissions resulted from SiC production while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2014 were 0.01 MMT CO₂ Eq. (0.4 kt CH₄) (see Table 4-32 and Table 4-33). Emissions have fluctuated in recent years, but 2014 emissions are only about 46 percent of emissions in 1990.

Table 4-32: CO₂ and CH₄ Emissions from Silicon Carbide Production and Consumption (MMT CO₂ Eq.)

Year	1990	2005	2010	2011	2012	2013	2014
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 CO₂ Eq.

Table 4-33: CO₂ and CH₄ Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2010	2011	2012	2013	2014
CO ₂	375	219	181	170	158	169	173
CH ₄	1	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO₂ and CH₄ from the production of SiC were calculated¹⁸ using the Tier 1 method provided by the *2006 IPCC Guidelines* (IPCC 2006). Annual estimates of SiC production were multiplied by the appropriate emission factor, as shown below:

$$E_{sc,CO_2} = EF_{sc,CO_2} \times Q_{sc}$$

$$E_{sc,CH_4} = EF_{sc,CH_4} \times Q_{sc} \times \left(\frac{1 \text{ metric ton}}{1000 \text{ kg}} \right)$$

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* (IPCC 2006):

- 2.62 metric tons CO₂/metric ton SiC
- 11.6 kg CH₄/metric ton SiC

Emissions of CO₂ from silicon carbide 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 (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Emissions of CO₂ from silicon carbide consumption for other non-abrasive uses were calculated by multiplying the annual SiC consumption for non-abrasive uses by the carbon content of SiC (31.5 percent). The annual SiC consumption for non-abrasive uses was calculated by multiplying the annual SiC consumption (production plus net imports) by the percent used in metallurgical and other non-abrasive uses (50 percent) (USGS 2006a) and then subtracting the SiC consumption for metallurgical use.

¹⁸ 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.

Production data for 1990 through 2013 were obtained from the *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2015b). Production data for 2014 were obtained from the *Minerals Industry Surveys: Abrasives (Manufactured)* (USGS 2015a). Silicon carbide consumption by major end use for 1990 through 2012 were obtained from the *Minerals Yearbook: Silicon* (USGS 1991b through 2013) (see Table 4-34). Silicon carbide consumption data for 2013 and 2014 are not yet publicly available and so 2012 data were used as proxy. Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2015).

Table 4-34: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
2005	35,000	220,149
2010	35,000	154,540
2011	35,000	136,222
2012	35,000	114,265
2013	35,000	134,055
2014	35,000	140,723

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 would be 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 CH₄, 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 methane 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 4-35. Silicon carbide production and consumption CO₂ emissions were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.17 MMT CO₂ Eq. at the 95 percent confidence level. Silicon carbide production CH₄ emissions were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.01 MMT CO₂ Eq. at the 95 percent confidence level.

Table 4-35: Approach 2 Quantitative Uncertainty Estimates for CH₄ and CO₂ Emissions from Silicon Carbide Production and Consumption (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	0.17	0.16	0.19	-9%	+9%
Silicon Carbide Production	CH ₄	+	+	+	-9%	+10%

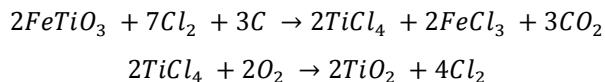
+ Does not exceed 0.05 MMT CO₂ Eq.

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.10 Titanium Dioxide Production (IPCC 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:



The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2 .

The C 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 2014, U.S. TiO_2 production totaled 1,310,000 metric tons (USGS 2015a). There were a total six plants producing TiO_2 in the United States—two located in Mississippi, and single plants located in Delaware, Louisiana, Ohio, and Tennessee.

Emissions of CO_2 from titanium dioxide production in 2014 were estimated to be 1.8 MMT CO_2 Eq. (1,755 kt CO_2), which represents an increase of 47 percent since 1990 (see Table 4-36).

Table 4-36: 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
2010	1.8	1,769
2011	1.7	1,729
2012	1.5	1,528
2013	1.7	1,715
2014	1.8	1,755

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* (IPCC 2006). 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

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 post-2004 production uses the chloride process (USGS 2005). The percentage of production from the chloride process is estimated at 100 percent since 2004. An emission factor of 1.34 metric tons CO₂/metric ton TiO₂ was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO₂ produced using the chloride process was produced using petroleum coke, although some TiO₂ may have been produced with graphite or other carbon inputs.

The emission factor for the TiO₂ chloride process was taken from the *2006 IPCC Guidelines* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO₂ production capacity that is chloride process for 1990 through 2013 (see Table 4-37) were obtained through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2015b). Production data for 2014 was obtained from the *Minerals Commodity Summary: Titanium and Titanium Dioxide* (USGS 2015a).¹⁹ Data on the percentage of total TiO₂ 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 4-37: Titanium Dioxide Production (kt)

Year	kt
1990	979
2005	1,310
2010	1,320
2011	1,290
2012	1,140
2013	1,280
2014	1,310

Uncertainty and Time-Series Consistency

Each year, the U.S. Geological Survey (USGS) collects titanium industry data for titanium mineral and pigment production operations. If TiO₂ pigment plants do not respond, production from the operations is estimated on the basis of prior year production levels and industry trends. Variability in response rates varies from 67 to 100 percent of TiO₂ pigment plants over the time series.

Although some TiO₂ 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 CO₂ per unit of TiO₂ produced as compared to that generated through the use of 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 TiO₂ 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 TiO₂ 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 TiO₂ production capacity that was attributed to the chloride process was multiplied by total TiO₂ production to estimate the amount of TiO₂ 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 TiO₂ production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO₂ chloride process; however, this composition information was not available.

¹⁹ 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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-38. Titanium dioxide consumption CO₂ emissions were estimated to be between 1.5 and 2.0 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.8 MMT CO₂ Eq.

Table 4-38: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Titanium Dioxide Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	1.8	1.5	2.0	-12%	+13%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Production data for 2013 were updated relative to the previous Inventory based on recently published data in the USGS *Minerals Yearbook: Titanium 2013* (USGS 2015b). This resulted in a 7 percent increase in 2013 CO₂ emissions from TiO₂ production relative to the previous report.

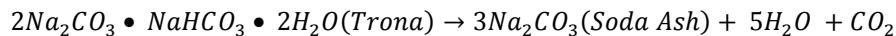
Planned Improvements

Planned improvements include researching the significance of titanium-slag production in electric furnaces and synthetic-rutile production using the Becher process in the United States. Significant use of these production processes will be included in future Inventories.

4.11 Soda Ash Production and Consumption (IPCC Source Category 2B7)

Carbon dioxide (CO₂) is generated as a byproduct of calcining trona ore to produce soda ash, and is eventually emitted into the atmosphere. In addition, CO₂ may also be released when soda ash is consumed. Emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for in the Energy sector.

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 CO₂ during trona-based production is based on the following reaction:



Soda ash (sodium carbonate, Na₂CO₃) 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. (Emissions from soda ash used in glass production are reported under IPCC Source Category 2A3. Glass production is its own source category and historical soda ash consumption figures have been adjusted to reflect this change.) After glass manufacturing, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2015b). 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-fourth of total world soda ash output. Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO₂ from Wyoming were calculated due to specifics regarding the production processes employed in the state.²⁰ Based on preliminary 2014 reported data, the estimated distribution of soda ash by end-use in 2014 (excluding glass production) was chemical production, 56 percent; soap and detergent manufacturing, 13 percent; distributors, 10 percent; flue gas desulfurization, 8 percent; other uses, 8 percent; pulp and paper production, 2 percent; and water treatment, 2 percent (USGS 2015a).

U.S. natural soda ash is competitive in world markets because the majority of the world output of soda ash is made synthetically. Although the United States continues to be a major supplier of world soda ash, China, which surpassed the United States in soda ash production in 2003, is the world's leading producer.

In 2014, CO₂ emissions from the production of soda ash from trona were approximately 1.7 MMT CO₂ Eq. (1,685 kt CO₂). Soda ash consumption in the United States generated 1.1 MMT CO₂ Eq. (1,143 kt CO₂) in 2014. Total emissions from soda ash production and consumption in 2014 were 2.8 MMT CO₂ Eq. (2,827 kt CO₂) (see Table 4-39 and Table 4-40).

Total emissions in 2014 increased by approximately 1 percent from emissions in 2013, and have stayed approximately the same as the 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 2014 since experiencing a decline in domestic and export sales caused by adverse global economic conditions in 2009. The annual average unit value of soda ash set a record high in 2013, and soda ash exports increased as well, accounting for 56 percent of total production (USGS 2015b).

Table 4-39: CO₂ Emissions from Soda Ash Production and Consumption Not Associated with Glass Manufacturing (MMT CO₂ Eq.)

Year	Production	Consumption	Total
1990	1.4	1.4	2.8
2005	1.7	1.3	3.0
2010	1.5	1.1	2.7
2011	1.6	1.1	2.7
2012	1.7	1.1	2.8
2013	1.7	1.1	2.8
2014	1.7	1.1	2.8

Note: Totals may not sum due to independent rounding.

²⁰ 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 CO₂ 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 CO₂ is generated as a byproduct, the CO₂ 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 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 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.

Table 4-40: CO₂ Emissions from Soda Ash Production and Consumption Not Associated with Glass Manufacturing (kt)

Year	Production	Consumption	Total
1990	1,431	1,390	2,822
2005	1,655	1,305	2,960
2010	1,548	1,148	2,697
2011	1,607	1,105	2,712
2012	1,665	1,097	2,763
2013	1,694	1,109	2,804
2014	1,685	1,143	2,827

Note: Totals may not sum due to independent rounding.

Methodology

During the 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 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 are required to generate one metric ton of CO₂, or an emission factor of 0.0974 metric tons CO₂ per metric ton trona (IPCC 2006). Thus, the 17.3 million metric tons of trona mined in 2014 for soda ash production (USGS 2015a) resulted in CO₂ emissions of approximately 1.7 MMT CO₂ Eq. (1,685 kt).

Once produced, most soda ash is consumed in chemical and soap production, with minor amounts in 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 CO₂ 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 CO₂) are released for every metric ton of soda ash consumed. In future Inventory reports, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, emissions from soda ash consumption in chemical production processes will be reported under Section 4.4 Other Process Uses of Carbonates (IPCC Category 2A4).

The activity data for trona production and soda ash consumption (see Table 4-41) for 1990 to 2014 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 2015a). Soda ash production and consumption data²¹ were collected by the USGS from voluntary surveys of the U.S. soda ash industry. The U.S. Environmental Protection Agency (EPA) will continue to analyze and assess opportunities to use facility-level data from EPA's Greenhouse Gas Reporting Program (GHGRP) to improve the emission estimates for Soda Ash Production source category consistent with IPCC²² and UNFCCC guidelines.

Table 4-41: Soda Ash Production and Consumption Not Associated with Glass Manufacturing (kt)

Year	Production ^a	Consumption ^b
1990	14,700	3,351

²¹ EPA has assessed feasibility of using emissions information (including activity data) from EPA's GHGRP program. However 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.

²² See <http://www.ipcc-nngip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

2005	17,000	3,144
2010	15,900	2,768
2011	16,500	2,663
2012	17,100	2,645
2013	17,400	2,674
2014	17,300	2,754

^a Soda ash produced from trona ore only.

^b 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

Emission estimates from soda ash production have relatively low associated uncertainty levels in that reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. Through EPA's GHGRP, EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process. 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 2014a). 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 1995). For emissions from soda ash consumption, the primary source of uncertainty, however, 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.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Soda Ash Production and Consumption CO₂ emissions were estimated to be between 2.5 and 2.9 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 6 percent above the emission estimate of 2.8 MMT CO₂ Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Soda Ash Production and Consumption (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Soda Ash Production and Consumption	CO ₂	2.8	2.5	2.9	-7%	+6%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculation Discussion

During the development of the current Inventory, an error in the transcription of the 2006 *IPCC Guidelines* default trona production emission factor was identified. This error was corrected in the current Inventory and resulted in a slight change of emissions over the entire time series (approximately 3 percent), compared with the previous Inventory.

Planned Improvements

In future Inventory reports, soda ash consumed for other chemical uses will be extracted from the current soda ash consumption emission estimates and included under those sources or Other Process Uses of Carbonates (IPCC Category 2A4).

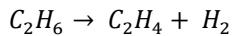
4.12 Petrochemical Production (IPCC Source Category 2B8)

The production of some petrochemicals results in the release of small amounts 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 2B5. 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.

Worldwide more than 90 percent of acrylonitrile (vinyl cyanide, $\text{C}_3\text{H}_3\text{N}$) 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, 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 also produces byproduct CO_2 , carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock, and produces other hydrocarbons from side reactions in the ammoxidation process.

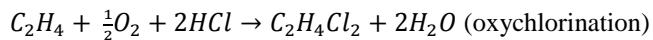
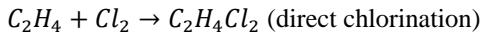
Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States 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. Carbon black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), by the thermal cracking of other hydrocarbons (i.e., thermal black process), and by the open burning of carbon black feedstock (i.e., lamp black process); each of these processes are used at only one U.S. plant each (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:



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 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:



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; however, in the United States only two facilities use steam reforming of natural gas. 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 2014 were 26.5 MMT CO_2 Eq. (26,509 kt CO_2) and 0.1 MMT CO_2 Eq. (5 kt CH_4), respectively (see Table 4-43 and Table 4-44). Since 1990, total CO_2 emissions from petrochemical production increased by approximately 23 percent. Methane emissions from petrochemical (methanol and acrylonitrile) production have decreased by approximately 43 percent since 1990, given declining production.

Table 4-43: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2010	2011	2012	2013	2014
CO_2	21.6	27.4	27.2	26.3	26.5	26.4	26.5
CH_4	0.2	0.1	+	+	0.1	0.1	0.1
Total	21.8	27.5	27.3	26.4	26.5	26.5	26.6

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-44: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2010	2011	2012	2013	2014
CO_2	21,609	27,380	27,246	26,326	26,464	26,437	26,509
CH_4	9	3	2	2	3	3	5

Methodology

Emissions of CO₂ and CH₄ were calculated using the estimation methods provided by the *2006 IPCC Guidelines* (IPCC 2006) and country-specific methods from EPA's Greenhouse Gas Reporting Program (GHGRP). The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO₂ and CH₄ emissions from production of acrylonitrile and methanol,²³ and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO₂ emissions from carbon black, ethylene, ethylene oxide, and ethylene dichloride. The Tier 2 method for petrochemicals is a total feedstock C mass balance method used to estimate total CO₂ emissions, but is not applicable for estimating CH₄ 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 CO₂. Further, the guideline states that while the total C mass balance method estimates total C emissions from the process but does not directly provide an estimate of the amount of the total C emissions emitted as CO₂, CH₄, or non-CH₄ volatile organic compounds (NMVOCs). This method accounts for all the C as CO₂, including CH₄. Note, a subset of facilities reporting under EPA's GHGRP use alternate methods to the C balance approach (e.g., Continuous Emission Monitoring Systems (CEMS) or other engineering approaches) to monitor CO₂ emissions and these facilities are required to also report CH₄ and N₂O emissions. Preliminary analysis of aggregated annual reports shows that these emissions are less than 500 kt/year and thus compilation of this information was not a priority for this report. Pending resources, EPA may include these emissions in future reports to enhance completeness.

Carbon Black, Ethylene, Ethylene Dichloride and Ethylene Oxide

2010-2014

Carbon dioxide emissions and national production were aggregated directly from EPA's GHGRP dataset for 2010 through 2014 (EPA GHGRP 2015). In 2014, GHGRP data reported CO₂ emissions of 3,272,934 metric tons from carbon black production; 18,805,943 metric tons of CO₂ from ethylene production; 591,127 metric tons of CO₂ from ethylene dichloride production; and 1,333,768 metric tons of CO₂ 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 CO₂ 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, 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 CO₂ emissions. The mass balance method is used by most facilities²⁴ and assumes that all the carbon input is converted into primary and secondary products, byproducts, or is emitted to the atmosphere as CO₂. To apply the mass

²³ 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.

²⁴ A few facilities producing ethylene dichloride used CO₂ CEMS, those CO₂ emissions have been included in the aggregated GHGRP emissions presented here. For ethylene production processes, nearly all process emissions are from the combustion of process off-gas. Under EPA's GHGRP, Subpart X, ethylene facilities can report CO₂ emissions from burning of process gases using the optional combustion methodology for ethylene production processes, which is requires estimating emissions based on fuel quantity and carbon contents of the fuel. This is consistent with the *2006 IPCC Guidelines* (p. 3.57) which recommends including combustion emissions from fuels obtained from feedstocks (e.g., off-gases) in petrochemical production under in the IPPU sector. In 2014, for example, this represented about 20 of the 80 reporting facilities. In addition to CO₂, these facilities are required to report emissions of CH₄ and N₂O from combustion of ethylene process off-gas in flares. Both facilities using CEMS (consistent with a Tier 3 approach) and those using the optional combustion methodology are also required to report emissions of CH₄ and N₂O from combustion of petrochemical process-off gases and flares, as applicable. Preliminary analysis of the aggregated reported CH₄ and N₂O emissions from facilities using CEMS and the optional combustion methodology suggests that these annual emissions are less than 500 kt/yr so not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these emissions in future reports to enhance completeness.

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. More details on the greenhouse gas calculation and monitoring methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part 98).²⁵

1990 through 2009

For prior years, for these petrochemical types, an average national CO₂ emission factor was calculated based on the 2010 through 2013 GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO₂ emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide. Carbon dioxide emission factors were derived from EPA's GHGRP data by dividing annual CO₂ 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 2014 (EPA GHGRP 2015). The average emission factors for each petrochemical type were applied across all prior years because 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 CO₂ emission factors that were calculated from the 2010 through 2014 GHGRP data are as follows:

- 2.59 metric tons CO₂/metric ton carbon black produced
- 0.79 metric tons CO₂/metric ton ethylene produced
- 0.040 metric tons CO₂/metric ton ethylene dichloride produced
- 0.46 metric tons CO₂/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 and ethylene dichloride for 1990 through 2009 were obtained from the American Chemistry Council's (ACC's) *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005 through 2011). Annual production data for ethylene oxide were obtained from ACC's *U.S. Chemical Industry Statistical Handbook* for 2003 through 2009 (ACC 2014a) and from ACC's *Business of Chemistry* for 1990 through 2002 (ACC 2014b). As noted above, annual 2010 through 2014 production data for carbon black, ethylene, ethylene dichloride, and ethylene oxide, were obtained from EPA's GHGRP (EPA GHGRP 2015).

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006). Annual acrylonitrile production data were used with IPCC default Tier 1 CO₂ and CH₄ emission factors to estimate emissions for 1990 through 2014. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH₄/metric ton acrylonitrile produced
- 1.00 metric tons CO₂/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2014 were obtained from ACC's *Business of Chemistry* (ACC 2015).

Methanol

Carbon dioxide and methane emissions from methanol production were estimated using Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006). Annual methanol production data were used with IPCC default Tier 1 CO₂ and CH₄ emission factors to estimate emissions for 1990 through 2014. Emission factors used to estimate methanol production emissions are as follows:

- 2.3 kg CH₄/metric ton methanol produced

²⁵ See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

- 0.67 metric tons CO₂/metric ton methanol produced

Annual methanol production data for 1990 through 2014 were obtained from the ACC's *Business of Chemistry* (ACC 2015).

Table 4-45: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2010	2011	2012	2013	2014
Carbon Black	1,307	1,651	1,309	1,338	1,283	1,228	1,207
Ethylene	16,542	23,975	24,355	25,143	24,763	25,341	25,509
Ethylene Dichloride	6,283	11,260	8,149	8,621	11,309	11,462	11,288
Ethylene Oxide	2,429	3,220	2,925	3,014	3,106	3,148	3,138
Acrylonitrile	1,214	1,325	1,160	1,055	1,220	1,075	1,095
Methanol	3,750	1,225	730	700	995	1,235	2,105

Uncertainty and Time-Series Consistency

The CH₄ and CO₂ 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 CO₂ 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 4-46. Petrochemical production CO₂ emissions were estimated to be between 25.3 and 27.8 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 26.5 MMT CO₂ Eq. Petrochemical production CH₄ emissions were estimated to be between 0.05 and 0.15 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 55 percent below to 45 percent above the emission estimate of 0.1 MMT CO₂ Eq.

Table 4-46: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Petrochemical Production and CO₂ Emissions from Carbon Black Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO ₂	26.5	25.3	27.8	-5%	+5%
Petrochemical Production	CH ₄	0.1	0.05	0.15	-55%	+45%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculation Discussion

Acrylonitrile production data were obtained from ACC (2015). The ACC data included annual production quantities for the 1990 through 2014 time series. These data included revised acrylonitrile production quantities for several years of the time series compared to the production data used in the previous Inventory. This update in the production data caused a change in acrylonitrile emissions compared to the previous Inventory report. As a result of this update, emissions for some years increased and emissions for other years decreased. The change in annual emissions from the previous Inventory ranged from -9 percent (in 2010) to 11 percent (in 2009).

Methanol production data for 1990 through 2014 were also obtained from ACC (2015). In the previous Inventory, methanol production data for 1990 through 2013 were obtained from ACC and Argus Media Inc. (ARGUS JJ&A 2014). As a result of this update, emissions for some years increased slightly and emissions for other years decreased slightly.

Planned Improvements

Improvements include further assessment of CH₄ and N₂O emissions to enhance completeness in reporting of emissions from petrochemical production, pending resources, significance and time series consistency considerations.

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 CO₂ estimates of non-energy use of fuels in the energy sector and CO₂ process emissions from petrochemical production in this sector. Data integration is not feasible at this time as feedstock data from the Energy Information Administration (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). EPA, through its GHGRP, currently does not collect complete data on quantities of fuel consumed as feedstocks by petrochemical producers, only feedstock type. Updates to reporting requirements may address this issue future reporting years for the GHGRP data allowing for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter.

4.13 HCFC-22 Production (IPCC Source Category 2B9a)

Trifluoromethane (HFC-23 or CHF₃) 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.²⁶ Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform (CHCl₃) and hydrogen fluoride (HF) in the presence of a catalyst, SbCl₅. 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

²⁶ 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]

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 U.S. in 2014. Emissions of HFC-23 from this activity in 2014 were estimated to be 5.0 MMT CO₂ Eq. (0.3 kt) (see Table 4-47). This quantity represents a 23 percent increase from 2013 emissions and an 89 percent decline from 1990 emissions. The increase from 2013 emissions and the decrease from 1990 emissions were caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). 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 factor was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

Table 4-47: HFC-23 Emissions from HCFC-22 Production (MMT CO₂ Eq. and kt HFC-23)

Year	MMT CO ₂ Eq.	kt HFC-23
1990	46.1	3
2005	20.0	1
2010	8.0	0.5
2011	8.8	0.6
2012	5.5	0.4
2013	4.1	0.3
2014	5.0	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 2014 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 to estimate their emissions 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. Plants that release (or historically have released) some of their byproduct HFC-23 periodically measure HFC-23 concentrations in the output stream 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, 2010). To estimate 2010 through 2014 emissions,

facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through the 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 4-48.

Table 4-48: HCFC-22 Production (kt)

Year	kt
1990	139
2005	156
2010	101
2011	110
2012	96
2013	C
2014	C

Note: HCFC-22 production in 2013 and 2014 is considered Confidential Business Information (CBI) as there were only two producers of HCFC-22 in 2013 and 2014.

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 2014. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the three plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants may have changed between 2006 and 2014 (because both HCFC-22 production and the HFC-23 emission rate declined significantly), the two plants that contribute significantly to emissions were estimated to have similar relative uncertainties in their 2006 (as well as 2005) emission estimates. Thus, changes in the relative contributions of these two plants to total emissions are 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 4-49. HFC-23 emissions from HCFC-22 production were estimated to be between 4.7 and 5.5 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 5.0 MMT CO₂ Eq.

Table 4-49: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	5.0	4.7	5.5	-7%	+10%

^a Range of emissions reflects a 95 percent confidence interval.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.14 Carbon Dioxide Consumption (IPCC 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). Carbon dioxide used for EOR is injected into the underground reservoirs to increase the reservoir pressure to enable additional petroleum to be produced. For the most part, CO_2 used in non-EOR applications will eventually be released to the atmosphere, and for the purposes of this analysis CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. Carbon dioxide used in EOR applications is discussed in the Energy chapter under “Carbon Capture and Storage, including Enhanced Oil Recovery” and is not discussed 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. Only CO_2 produced from naturally occurring CO_2 reservoirs, and as a byproduct from energy and industrial processes, and used in industrial applications other than EOR is included in this analysis. Carbon dioxide captured from biogenic sources (e.g., ethanol production plants) is not included in the Inventory. Carbon dioxide captured from crude oil and gas production is used in EOR applications and is therefore reported in the Energy chapter.

Carbon dioxide is produced as a byproduct of crude oil and natural gas production. This CO_2 is separated from the crude oil and natural gas using gas processing equipment, and may be emitted directly to the atmosphere, or captured and reinjected into underground formations, used for EOR, or sold for other commercial uses. A further discussion of CO_2 used in EOR is described in the Energy chapter under the text box titled “Carbon Dioxide Transport, Injection, and Geological Storage.”

In 2014, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 4.5 MMT CO_2 Eq. (4,471 kt) (see Table 4-50). This is an increase of approximately 7 percent from the previous year and an increase of approximately 204 percent since 1990.

Table 4-50: 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
2010	4.4	4,425
2011	4.1	4,083
2012	4.0	4,019
2013	4.2	4,188
2014	4.5	4,471

Methodology

Carbon dioxide emission estimates for 1990 through 2014 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 CO₂ production used in commercial applications other than EOR is eventually released into the atmosphere.

2010 through 2014

For 2010 through 2014, data from EPA's Greenhouse Gas Reporting Program (GHGRP) (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the Inventory (EPA GHGRP 2015). Facilities report CO₂ extracted or produced from natural reservoirs and industrial sites, and CO₂ captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO₂ transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO₂ 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 confidential business information (CBI). Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO₂ that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality issues and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO₂ 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 98.²⁷ The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2014 is much higher (ranging from 44 to 48) 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 CO₂ transferred to end-use applications from naturally occurring CO₂ reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO₂ production data from four naturally-occurring CO₂ reservoirs were used to estimate annual CO₂ 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 CO₂ for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO₂ 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 4-51). Denbury Resources reported the average CO₂ production in units of MMCF CO₂ per day for 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.

²⁷ See <http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl>.

Table 4-51: CO₂ Production (kt CO₂) 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
2010	NA	NA	NA	NA	64,724	7%
2011	NA	NA	NA	NA	66,241	6%
2012	NA	NA	NA	NA	66,326	6%
2013	NA	NA	NA	NA	68,435	6%
2014	NA	NA	NA	NA	71,431	6%

+ Does not exceed 0%.

^a Includes only food & beverage applications.

NA (Not available). For 2010 through 2014, the publicly available GHGRP data were aggregated at the national level.

Facility-level data are not publicly available from EPA's GHGRP.

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 CO₂ consumed for food and beverage applications given a threshold for reporting under GHGRP applicable to those reporting under Subpart PP, in addition to the exclusion of the amount of CO₂ transferred to all other end-use categories. This latter category might include CO₂ 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 CO₂ suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-52. Carbon dioxide consumption CO₂ emissions for 2014 were estimated to be between 3.9 and 5.1 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below to 13 percent above the emission estimate of 4.5 MMT CO₂ Eq.

Table 4-52: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from CO₂ Consumption (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	4.5	3.9	5.1	-12%	+13%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve accuracy and completeness of estimates for this source category. 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

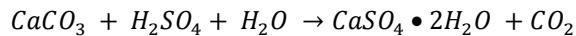
EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.²⁸

4.15 Phosphoric Acid Production (IPCC 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, North Carolina, Idaho, and Utah and is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies depending upon 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 also may contain organic carbon. The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic carbon that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry.

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). However, the generation of CO_2 is due to the associated limestone-sulfuric acid reaction, as shown below:



Total U.S. phosphate rock production sold or used in 2014 was 28.1 million metric tons (USGS 2015a). Approximately 80 percent of domestic phosphate rock production was mined in Florida and North Carolina, while the remaining 20 percent of production was mined in Idaho and Utah. Total imports of phosphate rock in 2014 were approximately 2.6 million metric tons (USGS 2015a). Most of the imported phosphate rock (74 percent) is from Morocco, with the remaining 26 percent being from Peru (USGS 2015a). All phosphate rock mining companies are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines. Some additional phosphoric acid production facilities are located in Texas, Louisiana, and Mississippi that used imported phosphate rock.

Over the 1990 to 2014 period, domestic production has decreased by nearly 44 percent. Total CO_2 emissions from phosphoric acid production were 1.1 MMT CO_2 Eq. (1,095 kt CO_2) in 2014 (see Table 4-53). Domestic consumption of phosphate rock in 2014 was estimated to have decreased by approximately 2 percent over 2013 levels, owing to producers drawing from higher than average inventories and the closure of a mine in Florida. Domestic consumption also decreased because of lower phosphoric acid and fertilizer production (USGS 2015a).

Table 4-53: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,529
2005	1.3	1,342
2010	1.1	1,087
2011	1.2	1,151
2012	1.1	1,093
2013	1.1	1,119
2014	1.1	1,095

²⁸ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

Methodology

Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO₂) 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 CO₂ emissions calculation methodology is based on the assumption that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to produce CO₂ 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 CO₂ and that all of the organic C content remains in the phosphoric acid product.

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 4-54). For the years 1990 through 1992, and 2005 through 2014, 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 average share of U.S. production in those states from 1993 to 2004 data. For the years 2005 through 2014, the same approximation method is used, but the share of U.S. production in those states data 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 2014 were obtained from USGS *Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2015b), and from USGS *Minerals Commodity Summaries: Phosphate Rock in 2015* (USGS 2015a). From 2004 through 2014, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2015b).

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 carbon. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-55).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO₂ emissions from consumption of phosphate rock mined in Florida and North Carolina (80 percent of domestic production) and carbonate content data for phosphate rock mined in Morocco are used to calculate CO₂ emissions from consumption of imported phosphate rock. The CO₂ emissions calculation is based on the assumption 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 2012b).

Table 4-54: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	1990	2005	2010	2011	2012	2013	2014
U.S. Domestic Consumption	49,800	35,200	28,100	28,600	27,300	28,800	28,100
FL and NC	42,494	28,160	22,480	22,880	21,840	23,040	22,480
ID and UT	7,306	7,040	5,620	5,720	5,460	5,760	5,620
Exports—FL and NC	6,240	0	0	0	0	0	0

Imports	451	2,630	2,400	3,350	3,080	2,560	2,570
Total U.S. Consumption	44,011	37,830	30,500	31,950	30,380	31,360	30,670

Table 4-55: 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 2014. For previous years in the time series, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2014 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2014 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 calculation are reported 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 CO₂ emissions from phosphoric acid production is the carbonate composition of phosphate rock; 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 the Florida Institute of Phosphate Research (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 CO₂ 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 CO₂. 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 approximately 7 percent of domestically-produced phosphate rock is used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2006). 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 CO₂ in the elemental phosphorus production process. The calculation for CO₂ emissions is based on the assumption that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO₂ 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 4-56. Phosphoric acid production CO₂ emissions were estimated to be between 0.9 and 1.4 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 20 percent above the emission estimate of 1.1 MMT CO₂ Eq.

Table 4-56: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Phosphoric Acid Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	1.1	0.9	1.4	-19%	+20%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Relative to the previous Inventory, the phosphate rock consumption data (sold or used and imports for consumption) for 2013 were revised based on updated data publicly available from USGS (USGS 2015). This revision caused a decrease in the 2013 emission estimate by approximately 2 percent.

Additionally, during the development of the current Inventory emission estimates, it was discovered that the phosphate rock CO₂ content had been incorrectly transcribed in the previous Inventory. This error was corrected in the current Inventory and resulted in a slight change of emissions over the entire 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 Greenhouse Gas Reporting Program (GHGRP) data for 2010 through 2014 and the use of reported GHGRP data to update the inorganic C content of phosphate rock for prior years. Confidentiality of CBI is being assessed, in addition to the applicability of EPA's GHGRP data for the averaged inorganic C content data (by region) from 2010 through 2014 to inform estimates in prior years in the required time series (i.e., 1990 through 2009). 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.²⁹

4.16 Iron and Steel Production (IPCC Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO₂) and methane (CH₄) 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 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. In addition to the production processes mentioned above, CO₂ is also generated at iron

²⁹ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

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 deducted and reported in the Energy chapter. In general, CO₂ emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). In addition, fugitive CH₄ emissions can also be generated from these processes but also sinter, direct iron and pellet production.

Currently, there are between 15 and 20 integrated iron and steel steelmaking facilities that utilize BOFs to refine and produce steel from iron and more than 100 steelmaking facilities that utilize EAFs to produce steel primarily from recycled ferrous scrap. In addition, there are 18 cokemaking facilities, of which 7 facilities are co-located with integrated iron and steel facilities. Slightly more than 62 percent of the raw steel produced in the United States is produced in one of seven states: Alabama, Arkansas, Indiana, Kentucky, Mississippi, Ohio, and Tennessee (AISI 2015a).

Total production of crude steel in the United States between 2000 and 2008 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. In 2010, crude steel production rebounded to 88,731,000 tons as economic conditions improved and then continued to increase to 95,237,000 tons in 2011 and 97,770,000 tons in 2012; crude steel production slightly decreased to 95,766,000 tons in 2013 and then slightly increased to 97,195,000 tons in 2014 (AISI 2015a). The United States was the third largest producer of raw steel in the world, behind China and Japan, accounting for approximately 5.3 percent of world production in 2013 (AISI 2015a).

The majority of CO₂ emissions from the iron and steel production process come from the use of 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.

According to the *2006 IPCC Guidelines* (IPCC 2006), 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. However, the approaches and emission estimates for both metallurgical coke production and iron and steel production are both 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 CO₂ from metallurgical coke production in 2014 were 1.9 MMT CO₂ Eq. (1,938 kt CO₂) (see Table 4-57 and Table 4-58). Emissions increased in 2014 from 2013 levels, but have decreased overall since 1990. Domestic coke production data for 2014 are not yet published and so 2013 data were used as proxy for 2014. Coke production in 2014 was 26 percent lower than in 2000 and 45 percent below 1990. Overall, emissions from metallurgical coke production have declined by 23 percent (0.6 MMT CO₂ Eq.) from 1990 to 2014.

Table 4-57: CO₂ Emissions from Metallurgical Coke Production (MMT CO₂ Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	2.5	2.0	2.1	1.4	0.5	1.8	1.9
Total	2.5	2.0	2.1	1.4	0.5	1.8	1.9

Table 4-58: CO₂ Emissions from Metallurgical Coke Production (kt)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	2,503	2,044	2,085	1,426	543	1,824	1,938

Iron and Steel Production

Emissions of CO₂ and CH₄ from iron and steel production in 2014 were 53.4 MMT CO₂ Eq. (53,417 kt) and 0.0094 MMT CO₂ Eq. (0.4 kt), respectively (see Table 4-59 through Table 4-62), totaling approximately 53.4 MMT CO₂ Eq. Emissions decreased in 2014 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 2014, domestic production of pig iron decreased by 3 percent from 2013 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2014 was 39 percent lower than in 2000 and 41 percent below 1990. Carbon dioxide emissions from steel production have decreased by 4 percent (0.3 MMT CO₂ Eq.) since 1990, while overall CO₂ emissions from iron and steel production have declined by 45 percent (43.7 MMT CO₂ Eq.) from 1990 to 2014.

Table 4-59: CO₂ Emissions from Iron and Steel Production (MMT CO₂ Eq.)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Sinter Production	2.4	1.7	1.0	1.2	1.2	1.1	1.1
Iron Production	45.6	17.5	17.8	18.4	10.9	11.9	16.8
Steel Production	7.9	9.4	9.2	9.3	9.9	8.6	7.6
Other Activities ^a	41.2	35.9	25.5	29.7	31.7	28.7	27.9
Total	97.2	64.5	53.6	58.5	53.7	50.4	53.4

^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.

Note: Totals may not sum due to independent rounding.

Table 4-60: CO₂ Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Sinter Production	2,448	1,663	1,045	1,188	1,159	1,117	1,104
Iron Production	45,592	17,545	17,802	18,375	10,917	11,934	16,754
Steel Production	7,933	9,356	9,235	9,255	9,860	8,617	7,648
Other Activities ^a	41,193	35,934	25,504	29,683	31,750	28,709	27,911
Total	97,166	64,499	53,586	58,501	53,686	50,378	53,417

^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.

Note: Totals may not sum due to independent rounding.

Table 4-61: CH₄ Emissions from Iron and Steel Production (MMT CO₂ Eq.)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Sinter Production	+	+	+	+	+	+	+
Total	+						

+ Does not exceed 0.05 MMT CO₂ Eq.

Table 4-62: CH₄ Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Sinter Production	0.9	0.6	0.4	0.4	0.4	0.4	0.4
Total	0.9	0.6	0.4	0.4	0.4	0.4	0.4

Methodology

Emission estimates presented in this chapter are largely based on Tier 2 methodologies provided by the *2006 IPCC Guidelines* (IPCC 2006). 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 and DRI production) for which available data are insufficient for utilizing a Tier 2 method.

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_{CO_2}	=	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:

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO_2} = Q_d \times EF_{d,CO_2}$$

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,CO_2}	=	Emissions from DRI production process for CO ₂ , metric ton
Q_d	=	Quantity of DRI produced, metric tons
EF_{d,CO_2}	=	Emission factor for CO ₂ , metric ton CO ₂ /metric ton DRI

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke that 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* (IPCC 2006) was utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze, coke oven gas, and coal tar) 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 4-63). 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 2008c; 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 4-63: Material Carbon Contents for Metallurgical Coke Production

Material	kg C/kg
Coal Tar	0.62
Coke	0.83
Coke Breeze	0.83
Coking Coal	0.73
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.

Although the 2006 *IPCC Guidelines* provide a Tier 1 CH₄ emission factor for metallurgical coke production (i.e., 0.1 g CH₄ per metric ton of coke production), it is not appropriate to use because CO₂ 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 C-containing output or as CO₂ emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH₄ emissions reported by coke production facilities under EPA's Greenhouse Gas Reporting Program (GHGRP). The assessment indicates that CH₄ emissions from coke production are below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA may include these emissions in future reports to enhance completeness.

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 2015a) (see Table 4-64). 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 2015a) and through personal communications with AISI (2008c) (see Table 4-65). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (2008c). 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). 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 coking coal, metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the 2006 *IPCC Guidelines* (IPCC 2006). The C content for coke breeze was assumed to equal the C content of coke.

Table 4-64: Production and Consumption Data for the Calculation of CO₂ and CH₄ Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014 ^a
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	19,135	19,445	18,825	19,481	19,481
Coke Production at Coke Plants	25,054	15,167	13,628	13,989	13,764	13,898	13,898
Coal Breeze Production	2,645	1,594	1,435	1,458	1,412	1,461	1,461
Coal Tar Production	1,058	638	574	583	565	584	584

^a 2013 data were used as a proxy because 2014 data are not yet published.

Table 4-65: Production and Consumption Data for the Calculation of CO₂ Emissions from Metallurgical Coke Production (Million ft³)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	95,405	109,044	113,772	108,162	102,899
Natural Gas Consumption	599	2,996	3,108	3,175	3,267	3,247	3,039
Blast Furnace Gas Consumption	24,602	4,460	3,181	3,853	4,351	4,255	4,346

Iron and Steel Production

Emissions of CO₂ from sinter production and direct reduced iron production were estimated by multiplying total national sinter production and the total national direct reduced iron production by Tier 1 CO₂ emission factors (see Table 4-66). Because estimates of sinter production and direct reduced iron production were not available, production was assumed to equal consumption.

Table 4-66: CO₂ Emission Factors for Sinter Production and Direct Reduced Iron Production

Material Produced	Metric Ton CO ₂ /Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7

Source: IPCC (2006), Table 4.1.

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, 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 4-67). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO₂ 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 direct reduced iron, pig iron, and flux additions 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, and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-67). 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 2008c]). The amount of flux (e.g., limestone and dolomite) used during steel manufacture was deducted from the Other Process Uses of Carbonates source category 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 4-67).

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 CO₂ emissions from iron and steel production (see Table 4-59 and Table 4-60).

Table 4-67: 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 CH₄, 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* (IPCC 2006) for sinter production (see Table 4-68). Although the *1995 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1995) provide a Tier 1 CH₄ emission factor for pig iron production, it is not appropriate to use because CO₂ 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 CO₂ emissions; the estimation of CH₄ emissions is precluded. A preliminary analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH₄ emissions are below 500 kt CO₂ Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron also results in emissions of CH₄ 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.

Table 4-68: CH₄ 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.

Sinter consumption data for 1990 through 2014 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2015a) and through personal communications with AISI (2008c) (see Table 4-69). 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 2014) and personal communication with the USGS Iron and Steel Commodity Specialist (Fenton 2015). 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 CO₂ emission factors for sinter production and direct reduced iron 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 2015a) and through personal communications with AISI (2008c) (see Table 4-69 and Table 4-70).

Data for EAF steel production, flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2015a) and through personal communications with AISI (2006 through 2015b and 2008c). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (2008c). 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 2015a) and through personal communications with AISI (2008c). 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 2014). 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 2015a) and through personal communications with AISI (2008c).

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 2015a). 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* (IPCC 2006). The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (2015b) and EPA (2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2015a). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2015a) and confirmed by AISI staff (Carroll 2015).

Table 4-69: Production and Consumption Data for the Calculation of CO₂ and CH₄ Emissions from Iron and Steel Production (Thousands Metric Tons)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Sinter Production							
Sinter Production	12,239	8,315	5,225	5,941	5,795	5,583	5,521
Direct Reduced Iron Production							
Direct Reduced Iron Production	516	1,303	1,441	1,582	3,530	3,350	2,113
Pig Iron Production							
Coke Consumption	24,946	13,832	10,883	11,962	9,571	9,308	11,136
Pig Iron Production	49,669	37,222	26,844	30,228	32,063	30,309	29,375
Direct Injection Coal Consumption	1,485	2,573	2,279	2,604	2,802	2,675	2,425
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,189	1,257	1,318	1,122	1,127
Scrap Steel Consumption	42,691	46,600	47,500	50,500	50,900	47,300	48,873
Flux Consumption	319	695	640	726	748	771	771
EAF Steel Production	33,511	52,194	49,339	52,108	52,415	52,641	55,174
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	31,200	31,300	31,500	29,600	23,755
Scrap Steel Consumption	14,713	11,400	9,860	8,800	8,350	7,890	5,917
Flux Consumption	576	582	431	454	476	454	454
BOF Steel Production	43,973	42,705	31,158	34,291	36,282	34,238	33,000

Table 4-70: Production and Consumption Data for the Calculation of CO₂ Emissions from Iron and Steel Production (Million ft³ unless otherwise specified)

Source/Activity Data	1990	2005	2010	2011	2012	2013	2014
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	47,814	59,132	62,469	48,812	47,734
Fuel Oil Consumption (thousand gallons)	163,397	16,170	27,505	21,378	19,240	17,468	16,674
Coke Oven Gas Consumption	22,033	16,557	14,233	17,772	18,608	17,710	16,896
Blast Furnace Gas Production	1,439,380	1,299,980	911,180	1,063,326	1,139,578	1,026,973	1,000,536
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	10,403	6,263	11,145	10,514	9,622
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	546	554	568	568	524
Other Activities							
Coke Oven Gas Consumption	224,883	97,132	80,626	90,718	94,596	89,884	85,479
Blast Furnace Gas Consumption	1,414,778	1,295,520	907,999	1,059,473	1,135,227	1,022,718	996,190

Uncertainty and Time-Series Consistency

The estimates of CO₂ emissions from metallurgical coke production are based on 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 CO₂ 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 CO₂ emissions from iron and steel production are based on material production and consumption data and average C contents. Current estimates include estimates from pellet consumption, but exclude emissions from pellet production. There is uncertainty associated with the assumption that direct reduced iron and sinter consumption are equal to production. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal; some of this coal may be used for electricity generation. 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. 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 CO₂ emissions. However, there are uncertainties associated with each.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-71 for metallurgical coke production and iron and steel production. Total CO₂ emissions from metallurgical coke production and iron and steel production were estimated to be between 47.2 and 63.6 MMT CO₂ Eq. at the 95 percent confidence level. This

indicates a range of approximately 15 percent below and 15 percent above the emission estimate of 55.4 MMT CO₂ Eq. Total CH₄ emissions from metallurgical coke production and iron and steel production were estimated to be between 0.008 and 0.01 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 19 percent above the emission estimate of 0.009 MMT CO₂ Eq.

Table 4-71: Approach 2 Quantitative Uncertainty Estimates for CO₂ and CH₄ Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	55.4	47.2	63.6	-15%	+15%
Metallurgical Coke & Iron and Steel Production	CH ₄	+	+	+	-19%	+19%

^a Does not exceed 0.05 MMT CO₂ 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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

Several adjustments were incorporated into the emission calculations for the Iron and Steel Production and Metallurgical Coke Production source categories. These adjustments applied to the entire time series from 1990 to 2014 and are briefly described below.

Previous Inventory reports included CH₄ emissions calculated using a Tier 1 CH₄ emission factor for two different production processes: metallurgical coke and pig iron. However, the use of a Tier 1 CH₄ emission factor was not applicable for the metallurgical coke and pig iron production processes in the United States, because the CO₂ emissions for these production processes were estimated using the Tier 2 mass balance methodology. The Tier 2 mass balance methodology makes a basic assumption that all carbon that enters the specific production process either exits the process as part of a carbon-containing output or as CO₂ emissions; the estimation of CH₄ emissions is necessarily precluded by definition. Because CO₂ emissions for the sinter production process were estimated using a Tier 1 CO₂ emission factor, it is still appropriate to use a Tier 1 CH₄ emission factor for the sinter production process. Due to exclusion of CH₄ emissions from the metallurgical coke and pig iron production processes, CH₄ emissions reported in the Inventory were significantly reduced. This assumption and the revisions are further supported by a preliminary analysis of annual facility-level CH₄ reported to EPA's GHGRP from the iron and coke production processes.

Previous Inventory reports have also relied significantly on activity data (i.e., production and input statistics) from AISI's *Annual Statistical Report* (AISI 2004 through 2015a); three key fuels used in the Tier 2 mass balance methodology were natural gas, coke oven gas, and blast furnace gas. For all three of these fuels, volumetric consumption was multiplied by a heat content to obtain the quantity of energy, which was then multiplied by carbon content to obtain the quantity of carbon. The heat content of natural gas was obtained from EIA's *Natural Gas Annual* (EIA 2015a) and varied from year to year with values ranging from 1,022 to 1,031 BTU/ft³, while the heat contents of coke oven gas (500 BTU/ft³) and blast furnace gas (90 BTU/ft³) were obtained from the report, *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). However, close examination of Table 37 of the AISI's *Annual Statistical Report* (AISI 2004 through 2015a) indicates that the reported quantities of natural gas and blast furnace gas have different reporting bases based on heat contents (i.e., 1,000 BTU/ft³ for natural gas and 95 BTU/ft³ for blast furnace gas); the reporting basis for coke oven gas is identically 500 BTU/ft³. AISI staff confirmed that the reporting bases included in Table 37 of the AISI's *Annual Statistical Report* (AISI 2004 through 2015a) have been used dating back to at least 1990. Therefore, the use of other heat contents with AISI's data is not appropriate. The heat content of natural gas was changed to 1,000 BTU/ft³ for all years in the time series and the heat content of blast furnace gas was changed to 95 BTU/ft³. Because blast furnace gas is used

as both an input and an output in the Tier 2 mass balance methodology, the use of revised heat contents for natural gas and blast furnace gas only resulted in a slight decrease in estimated CO₂ emissions; however, the CO₂ emissions for individual production processes did change noticeably. For instance, across the entire time series, an increase in CO₂ emissions from heating, annealing, and other processes was essentially offset by a decrease in CO₂ emissions from the iron production process.

Planned Improvements

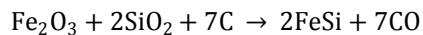
Future improvements involve improving completeness by including emissions from pellet production. The current version of the Inventory includes pellet consumption within the iron & steel sector, but does not include greenhouse gas emissions from pellet production. The EPA has identified a potential activity data source for national-level pellet production and will include this emission source in the future versions of the Inventory. EPA will also evaluate and analyze data reported under EPA's GHGRP by taconite indurating furnaces 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.³⁰

Additional improvements include accounting for emission estimates for the production of metallurgical coke to 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 Industrial Processes and Product Use chapters.

4.17 Ferroalloy Production (IPCC Source Category 2C2)

Carbon dioxide (CO₂) and methane (CH₄) 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, CO₂ 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 CO₂. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:



While most of the carbon contained in the process materials is released to the atmosphere as CO₂, a percentage is also released as CH₄ and other volatiles. The amount of CH₄ that is released is dependent on furnace efficiency, operation technique, and control technology.

³⁰ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

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. Twelve companies in the United States produce ferroalloys (USGS 2015a).

Emissions of CO₂ from ferroalloy production in 2014 were 1.9 MMT CO₂ Eq. (1,914 kt CO₂) (see Table 4-72 and Table 4-73), which is an 11 percent reduction since 1990. Emissions of CH₄ from ferroalloy production in 2014 were 0.01 MMT CO₂ Eq. (0.5 kt CH₄), which is a 21 percent decrease since 1990.

Table 4-72: CO₂ and CH₄ Emissions from Ferroalloy Production (MMT CO₂ Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	2.2	1.4	1.7	1.7	1.9	1.8	1.9
CH ₄	+	+	+	+	+	+	+
Total	2.2	1.4	1.7	1.7	1.9	1.8	1.9

+ Does not exceed 0.05 MMT CO₂ Eq.

Table 4-73: CO₂ and CH₄ Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	2,152	1,392	1,663	1,735	1,903	1,785	1,914
CH ₄	1	+	+	+	1	+	1

+ Does not exceed 0.5 kt.

Methodology

Emissions of CO₂ and CH₄ from ferroalloy production were calculated³¹ using a Tier 1 method from the *2006 IPCC Guidelines* (IPCC 2006) by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (2006). The Tier 1 equations for CO₂ and CH₄ emissions are as follows:

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

where,

- E_{CO_2} = CO₂ emissions, metric tons
 MP_i = Production of ferroalloy type i , metric tons
 EF_i = Generic emission factor for ferroalloy type i , metric tons CO₂/metric ton specific ferroalloy product

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

- E_{CH_4} = CH₄ emissions, kg
 MP_i = Production of ferroalloy type i , metric tons
 EF_i = Generic emission factor for ferroalloy type i , kg CH₄/metric ton specific ferroalloy product

³¹ 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.

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO₂ and CH₄ estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si – 2.5 metric tons CO₂/metric ton of alloy produced; 1.0 kg CH₄/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si – 4.0 metric tons CO₂/metric ton alloy produced; 1.0 kg CH₄/metric ton of alloy produced.
- Silicon Metal – 5.0 metric tons CO₂/metric ton metal produced; 1.2 kg CH₄/metric ton metal produced.

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).

Ferroalloy production data for 1990 through 2014 (see Table 4-74) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2013) and the *Mineral Industry Surveys: Silicon* (USGS 2014, 2015b). 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 to 1999. Starting 2000, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS reported 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 2014 (USGS 2013, 2014, 2015b).

Table 4-74: 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
2010	153,000	135,000	148,000	NA
2011	159,667	140,883	154,450	NA
2012	175,108	154,507	169,385	NA
2013	164,229	144,908	158,862	NA
2014	176,161	155,436	170,404	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.

Also, 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.³² 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 CO₂ 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 CH₄ 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 will reduce CH₄ emissions; however, specific furnace information was not available or included in the CH₄ emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-75. Ferroalloy production CO₂ emissions were estimated to be between 1.7 and 2.1 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.9 MMT CO₂ Eq. Ferroalloy production CH₄ emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 MMT CO₂ Eq.

Table 4-75: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Ferroalloy Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	1.9	1.7	2.1	-12%	+12%
Ferroalloy Production	CH ₄	+	+	+	-12%	+12%

+ Does not exceed 0.05 MMT CO₂ 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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Ferroalloy Production source category. 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.³³

³² Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

³³ See <http://www.ipcc-nrgip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

4.18 Aluminum Production (IPCC 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 sixth largest producer of primary aluminum, with approximately 3 percent of the world total production (USGS 2015a). 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 2.8 MMT CO_2 Eq. (2,833 kt) in 2014 (see Table 4-76). 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 4-76: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	6.8	6,831
2005	4.1	4,142
2010	2.7	2,722
2011	3.3	3,292
2012	3.4	3,439
2013	3.3	3,255
2014	2.8	2,833

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 “anode effects.” These anode effects 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.

Since 1990, emissions of CF_4 and C_2F_6 have declined by 89 percent and 83 percent, respectively, to 1.9 MMT CO_2 Eq. of CF_4 (0.3 kt) and 0.6 MMT CO_2 Eq. of C_2F_6 (0.1 kt) in 2014, as shown in Table 4-77 and Table 4-78. 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 58 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 72 percent. Emissions decreased by approximately 18 percent between 2013 and 2014 due to decreases in aluminum production and in the rate of CF_4 and C_2F_6 emissions per metric ton of aluminum produced.

Table 4-77: PFC Emissions from Aluminum Production (MMT CO₂ Eq.)

Year	CF ₄	C ₂ F ₆	Total
1990	17.9	3.5	21.5
2005	2.9	0.6	3.4
2010	1.4	0.5	1.9
2011	2.7	0.8	3.5
2012	2.3	0.7	2.9
2013	2.3	0.7	3.0
2014	1.9	0.6	2.5

Note: Totals may not sum due to independent rounding.

Table 4-78: PFC Emissions from Aluminum Production (kt)

Year	CF ₄	C ₂ F ₆
1990	2.4	0.3
2005	0.4	+
2010	0.2	+
2011	0.4	0.1
2012	0.4	0.1
2013	0.3	0.1
2014	0.3	0.1

+ Does not exceed 0.05 kt.

In 2014, U.S. primary aluminum production totaled approximately 1.7 million metric tons, a 12 percent decrease from 2013 production levels (USAA 2015). In 2014, three companies managed production at nine operational primary aluminum smelters. Four smelters were closed for the entire year in 2014 (USGS 2015b). During 2014, monthly U.S. primary aluminum production was lower for every month in 2014, when compared to the corresponding months in 2013 (USGS 2015c; USGS 2014).

For 2015, total production was approximately 1.6 million metric tons compared to 1.7 million metric tons in 2014, a 7 percent decrease (USAA 2016). Based on the decrease in production, process CO₂ and PFC emissions are likely to be lower in 2015 compared to 2014 if there are no significant changes in process controls at operational facilities.

Methodology

Process CO₂ and PFC—i.e., CF₄ and C₂F₆—emission estimates from primary aluminum production for 2010 through 2014 are available from EPA’s Greenhouse Gas Reporting Program (GHGRP)—Subpart F (Aluminum Production) (EPA 2016). Under EPA’s GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2014) are available to be incorporated into the Inventory. EPA’s GHGRP mandates that all facilities that contain an aluminum production process must report: CF₄ and C₂F₆ emissions from anode effects in all prebake and Søderberg electrolysis cells, CO₂ emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO₂ emissions from onsite anode baking. To estimate the process emissions, EPA’s GHGRP uses the process-specific equations (and certain technology-specific defaults) detailed in subpart F (aluminum production).³⁴ 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

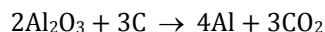
³⁴ Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See <www.epa.gov/ghgreporting/documents/pdf/infosheets/aluminumproduction.pdf>.

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.

Process CO₂ 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 with IPCC (2006) 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 CO₂ emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction:



For prebake smelter technologies, CO₂ is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO₂ emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO₂ 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 CO₂ emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all C in the anode is converted to CO₂. 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 (2006), and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO₂ 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 Söderberg 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 CO₂ 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 CO₂ emissions data or CO₂ 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), CO₂ emission estimates were estimated using Tier 1 Söderberg and/or Prebake emission factors (metric ton of CO₂ per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2014 were reported to EPA under its GHGRP. To estimate their PFC emissions 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 ₂ F 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. 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.

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 (from USGS and USAA), with allocation to specific smelters based on reported production capacities (from USGS).

National primary aluminum production data for 2014 were obtained via USAA (2015). For 1990 through 2001, and 2006 (see Table 4-79) 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 2013, national aluminum production data were obtained from the USAA's Primary Aluminum Statistics (USAA 2004 through 2006, 2008 through 2014).

Table 4-79: Production of Primary Aluminum (kt)

Year	kt
1990	4,048
2005	2,478
2009	1,727
2010	1,727
2011	1,986
2012	2,070
2013	1,948
2014	1,710

Uncertainty and Time-Series Consistency

Uncertainty was assigned to the CO₂, CF₄, and C₂F₆ emission values reported by each individual facility to EPA's GHGRP. As previously mentioned, the methods for estimating emissions for EPA's GHGRP and this report are the same, and follow the IPCC (2006) methodology. As a result, it was possible to assign uncertainty bounds (and distributions) based on an analysis of the uncertainty associated with the facility-specific emissions estimated for previous Inventory years. Uncertainty surrounding the reported CO₂, CF₄, and C₂F₆ emission values were determined to have a normal distribution with uncertainty ranges of ±6, ±16, and ±20 percent, respectively. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO₂, CF₄, and C₂F₆ 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 4-80. Aluminum production-related CO₂ emissions were estimated to be between 2.8 and 2.9 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below to 2 percent above the emission estimate of 2.8 MMT CO₂ Eq. Also, production-related CF₄ emissions were estimated to be between 1.8 and 2.0 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 7 percent above the emission estimate of 1.9 MMT CO₂ Eq. Finally, aluminum production-related C₂F₆ emissions were estimated to be between 0.5 and 0.7 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below to 13 percent above the emission estimate of 0.6 MMT CO₂ Eq.

Table 4-80: Approach 2 Quantitative Uncertainty Estimates for CO₂ and PFC Emissions from Aluminum Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	2.8	2.8	2.9	-2%	+2%
Aluminum Production	CF ₄	1.9	1.8	2.0	-7%	+7%
Aluminum Production	C ₂ F ₆	0.6	0.5	0.7	-13%	+13%

^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 2014. 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 the Aluminum Production category 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.

4.19 Magnesium Production and Processing (IPCC Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF₆) 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 SF₆ with dry air and/or carbon dioxide (CO₂) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF₆ reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF₆ reacting in magnesium production and processing is considered to be negligible and thus all SF₆ 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 (SO₂) systems can, and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF₆ cover gas systems.

The magnesium industry emitted 1.0 MMT CO₂ Eq. (0.05 kt) of SF₆, 0.14 MMT CO₂ Eq. (0.10 kt) of HFC-134a, and 0.002 MMT CO₂ Eq. (2.3 kt) of CO₂ in 2014. This represents a decrease of approximately 24 percent from total 2013 emissions (see Table 4-81). The decrease can be attributed to reduction in primary, secondary, and die casting SF₆ emissions between 2013 and 2014 as reported through EPA's Greenhouse Gas Reporting Program (GHGRP), with the largest absolute reduction being seen for primary emissions. The reduction in SF₆ emissions is likely due in part to decreased production from reporting facilities in 2014. The decrease in SF₆ emissions can also be attributed to continuing industry efforts to utilize SF₆ alternatives, such as HFC-134a, Novec™612 and SO₂, to reduce greenhouse gas emissions. In 2014, the emissions of HFC-134a increased by 75 percent compared to 2013 emissions mainly due to the increased use of this alternative for primary production. In 2014, total HFC-134a emissions increased from 0.08 MMT CO₂ Eq. to 0.14 MMT CO₂ Eq., while the FK 5-1-12 emissions were constant. The emissions of the carrier gas, CO₂, increased from 2.1 kt in 2013 to 2.3 kt in 2014.

Table 4-81: SF₆, HFC-134a, FK 5-1-12 and CO₂ Emissions from Magnesium Production and Processing (MMT CO₂ Eq.)

Year	1990	2005	2010	2011	2012	2013	2014
SF ₆	5.2	2.7	2.1	2.8	1.6	1.5	1.0
HFC-134a	0.0	0.0	+	+	+	0.1	0.1
CO ₂	+	+	+	+	+	+	+
FK 5-1-12	0.0	0.0	+	+	+	+	+
Total^a	5.2	2.8	2.1	2.8	1.7	1.5	1.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Total does not include FK 5-1-12. FK-5-1-12 values shown for informational purposes only.

Note: Totals may not sum due to independent rounding.

Table 4-82: SF₆, HFC-134a, FK 5-1-12 and CO₂ Emissions from Magnesium Production and Processing (kt)

Year	1990	2005	2010	2011	2012	2013	2014
SF ₆	0.2	0.1	0.1	0.1	0.1	0.1	+
HFC-134a	0.0	0.0	+	+	+	0.1	0.1
CO ₂	1.4	2.9	1.3	3.1	2.3	2.1	2.3
FK 5-1-12	0.0	0.0	+	+	+	+	+

+ Does not exceed 0.05 kt.

Methodology

Emission estimates for the magnesium industry incorporate information provided by some 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 the 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 was assumed to be equivalent to emissions. Along with SF₆, some Partners also reported their HFC-134a and FK 5-1-12 usage, which is assumed to be equal to emissions. 2010 was the last reporting year under the Partnership. Emissions data for 2011 through 2014 were 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, 1999 through 2010, and 2011 through 2014. The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS).

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 is reported in the RAND survey of major SF₆ manufacturers, which shows 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 4-81. These 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 is then applied to the CO₂ emissions of the subsequent year to determine the CO₂ 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 SF₆ 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 are 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 and from 2008 through 2010, Partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not Partners. 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 SF₆ 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 SF₆ per metric ton of magnesium. This emission factor was developed using magnesium production and SF₆ usage data for the year 1999. For 2008 through 2010, the characteristics of the die casters who were not Partners were not well known, and therefore the emission factor for these die casters was set equal to 3.0 kg SF₆ per metric ton of magnesium, the average of the emission factors reported over the same period by the die casters who were Partners.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF₆ 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 SF₆ 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 4-83.

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 CO₂ 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 (SF₆, 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 CO₂ 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 4-83: SF₆ Emission Factors (kg SF₆ per metric ton of magnesium)

Year	Die Casting ^a	Permanent Mold	Wrought	Anodes
1999	2.14 ^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	0.10	2	1	1
2009	2.30	2	1	1
2010	2.94	2	1	1

^a Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000-2007), 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 SF₆ per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2014

For 2011 through 2014, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For die and sand casting, some emissions data was obtained through EPA's GHGRP. The balance of the emissions for these industry segments were 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 SF₆ at the last reported level, which was from 2010 in most cases. 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. 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 2014).

Uncertainty and Time-Series Consistency

Uncertainty surrounding the total estimated emissions in 2014 is attributed to the uncertainties around SF₆, HFC-134a, and CO₂ emission estimates. To estimate the uncertainty surrounding the estimated 2014 SF₆ emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2014 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2014 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 reporting program, SF₆ 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. Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP program. One known sand caster (the lone Partner) has not reported since 2007 and its activity and emission factor were held constant at 2005 levels due to a reporting anomaly in 2006 because of malfunctions at the facility. The uncertainty associated with the SF₆ usage for the sand casting Partner was 85 percent. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF₆ emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-84). 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 uncertainties 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 SF₆ 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 SF₆ 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 4-84. Total emissions associated with magnesium production and processing were estimated to be between 1.1 and 1.3 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 10 percent above the 2014 emission estimate of 1.2 MMT CO₂ Eq. The uncertainty estimates for 2014 are similar relative to the uncertainty reported for 2013 in the previous Inventory report.

Table 4-84: Approach 2 Quantitative Uncertainty Estimates for SF₆, HFC-134a and CO₂ Emissions from Magnesium Production and Processing (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	1.2	1.1	1.3	-9%	+10%

^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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For one facility, a recalculation for 2013 SF₆ and CO₂ emissions was performed to ensure methodological consistency. The emissions for this facility and year were previously held constant at 2012 levels based on data reported through the GHGRP. This estimate has been revised by interpolating the reported emissions between 2012 and 2014, reported via EPA's GHGRP. This has caused a slight decrease in the SF₆ emissions and slight increase in CO₂ emissions for 2013 compared to the previous Inventory.

Planned Improvements

Cover gas research conducted over the last decade has found that SF₆ 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 SF₆ 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, it will be determined if CO₂ carrier gas emissions are to be estimated.

4.20 Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes—both of which emit carbon dioxide (CO₂) (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 CO₂ 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 end of 2013. In 2014, the smelter processed a small amount of residual lead during demolition of the site (USGS 2015).

Similar to primary lead production, CO₂ 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. Of all the domestic secondary smelters operational in 2014, 12 smelters had capacities of 30,000 tons or more and were

collectively responsible for more than 95 percent of secondary lead production in 2014 (USGS 2015). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2014, secondary lead production accounted for nearly 100 percent of total lead production. The lead-acid battery industry accounted for about 90 percent of the reported U.S. lead consumption in 2014 (USGS 2015).

In 2014, total secondary lead production in the United States was slightly greater than that in 2013. Increased production at a couple of smelters was offset by temporary closure of one smelter. In March 2014, a producer temporarily shut down operations of a lead smelter in Vernon, CA (90,000 metric ton capacity smelter) due to environmental concerns from state regulators. The company intends to restart operations in 2015, after making improvements to the plant. Increases in exports of spent lead-acid batteries in recent years have decreased the amount of scrap available to secondary smelters (USGS 2015).

U.S. primary lead production decreased by approximately 99 percent from 2013 to 2014, and has decreased by almost 100 percent since 1990. This is due to the closure of the only domestic primary lead smelter in 2013 (year-end). In 2014, U.S. secondary lead production was unchanged from 2013 levels, and has increased by 25 percent since 1990 (USGS 1995 through 2013, 2014, 2015).

In 2014, U.S. primary and secondary lead production totaled 1,151,000 metric tons (USGS 2015). The resulting emissions of CO₂ from 2014 lead production were estimated to be 0.5 MMT CO₂ Eq. (518 kt) (see Table 4-85). The majority of 2014 lead production is from secondary processes, which accounted for almost 100 percent of total 2014 CO₂ emissions from lead production. At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for approximately 7 percent of world production in 2014 (USGS 2015).

Table 4-85: CO₂ Emissions from Lead Production (MMT CO₂ Eq. and kt)

Year	MMT CO ₂ Eq.	kt
1990	0.5	516
2005	0.6	553
2010	0.5	542
2011	0.5	538
2012	0.5	527
2013	0.5	546
2014	0.5	518

After a steady increase in total emissions from 1995 to 2000, total emissions have gradually decreased since 2000 and are currently at the 1990 levels.

Methodology

The methods used to estimate emissions for lead production³⁵ are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation is as follows:

$$CO_2 \text{ Emissions} = (DS \times EF_{DS}) + (S \times EF_S)$$

where,

- DS = Lead produced by direct smelting, metric ton
- S = Lead produced from secondary materials
- EF_{DS} = Emission factor for direct Smelting, metric tons CO₂/metric ton lead product

³⁵ 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.

$$EF_s = \text{Emission factor for secondary materials, metric tons CO}_2/\text{metric ton lead product}$$

For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO₂/metric ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.25 metric tons CO₂/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO₂/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 CO₂ emissions.

The 1990 through 2014 activity data for primary and secondary lead production (see Table 4-86) were obtained from the U.S. Geological Survey (USGS 1995 through 2013, 2014, 2015).

Table 4-86: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2010	115,000	1,140,000
2011	118,000	1,130,000
2012	111,000	1,110,000
2013	114,000	1,150,000
2014	1,000	1,150,000

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 CO₂ 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. This information is collected by USGS via voluntary surveys.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-87. Lead production CO₂ emissions were estimated to be between 0.4 and 0.6 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.5 MMT CO₂ Eq.

Table 4-87: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Lead Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Lead Production	CO ₂	0.5	0.4	0.6	-15%	+16%

^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 consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

For the current Inventory, primary and secondary lead production quantities were revised to reflect the most recent USGS publication (USGS 2015). In the previous Inventory report, the 2013 primary and secondary lead production quantities were based on preliminary USGS estimates that were available at the time. This change resulted in a 4 percent increase in the 2013 emission estimate compared to the previous Inventory report.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Lead Production source category. 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.³⁶

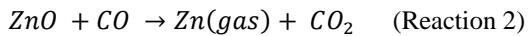
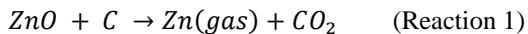
4.21 Zinc Production (IPCC Source Category 2C6)

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.



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 1100 to 1200 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

³⁶ See <http://www.ipcc-nngip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

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 CO₂ 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 Horsehead, PIZO, and Steel Dust Recycling. For Horsehead, EAF dust is recycled in Waelz kilns at their Beaumont, TX; Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. These Waelz kiln 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, Horsehead permanently shut down their Monaca smelter. This was replaced by their new facility in Mooresboro, NC. The new Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products. The current capacity of the new facility is 155,000 short tons, with plans to expand to 170,000 short tons per year. 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). Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

PIZO and Steel Dust Recycling recycle EAF dust into intermediate zinc products using Waelz kilns, and then sell the intermediate products to companies who smelt it into refined products.

In 2014, U.S. primary and secondary refined zinc production were estimated to total 185,000 metric tons (USGS 2015) (see Table 4-88). Domestic zinc mine production increased slightly in 2014 compared to 2013 levels, primarily owing to an increase in zinc production at the Red Dog mine in Alaska. Zinc metal production decreased by 20 percent owing to a decline in secondary production; Horsehead closed its smelter in Monaca, PA, while starting up its new recycling facility in Mooresboro, NC. However, the new facility experienced delayed ramp-up efforts due to technical issues and did not reach optimum production levels until the end of 2014 (USGS 2015). Primary zinc production (primary slab zinc) increased slightly in 2014, while, secondary zinc production in 2014 decreased relative to 2013.

Emissions of CO₂ from zinc production in 2014 were estimated to be 1.0 MMT CO₂ Eq. (956 kt CO₂) (see Table 4-89). All 2014 CO₂ 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 2014, emissions were estimated to be 51 percent higher than they were in 1990.

Table 4-88: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	95,708
2005	191,120	156,000
2010	120,000	129,000
2011	110,000	138,000
2012	114,000	147,000
2013	106,000	127,000
2014	115,000	70,000

Table 4-89: CO₂ Emissions from Zinc Production (MMT CO₂ Eq. and kt)

Year	MMT CO ₂ Eq.	kt
1990	0.6	632
2005	1.0	1,030
2010	1.2	1,182
2011	1.3	1,286
2012	1.5	1,486
2013	1.4	1,429
2014	1.0	956

Methodology

The methods used to estimate non-energy CO₂ emissions from zinc production³⁷ 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:

$$E_{CO_2} = Zn \times EF_{default}$$

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 coke consumption factors and other data presented in Viklund-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:

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

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:

³⁷ 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.

$$EF_{EAF\ Dust} = \frac{0.4 \text{ metric tons coke}}{\text{metric tons EAF Dust}} \times \frac{0.85 \text{ metric tons C}}{\text{metric tons coke}} \times \frac{3.67 \text{ metric tons CO}_2}{\text{metric tons C}} = \frac{1.24 \text{ metric tons CO}_2}{\text{metric tons EAF Dust}}$$

The total amount of EAF dust consumed by Horsehead at their Waelz kilns was available from Horsehead financial reports for years 2006 through 2014 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, and 2015).

Consumption levels for 1990 through 2005 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). The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO₂/metric ton EAF dust consumed emission factor to develop CO₂ emission estimates for Horsehead's Waelz kiln facilities.

The amount of EAF dust consumed by Steel Dust Recycling (SDR) and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2014 (SDR 2012, 2014, and 2015). SDR's facility in Alabama underwent expansion in 2011 to include a second unit (operational since early- to mid-2012). SDR's facility has been operational since 2008. Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for Horsehead's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using Horsehead's annual consumption and total capacity for the years 2008 through 2010. Horsehead'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).

PIZO Technologies Worldwide LLC's facility in Arkansas has been operational since 2009. The amount of EAF dust consumed by PIZO's facility for 2009 through 2014 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of Horsehead'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 2014 were estimated by applying the average annual capacity utilization rates for Horsehead and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012, 2013, 2014, and 2015; SDR 2012 and 2014; PIZO 2012 and 2014). The 1.24 metric tons CO₂/metric ton EAF dust consumed emission factor was then applied to PIZO's and Steel Dust Recycling's estimated EAF dust consumption to develop CO₂ emission estimates for those Waelz kiln facilities.

Refined zinc production levels for Horsehead'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 was replaced by Horsehead's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. This process is assumed to be non-emissive. Production levels for 1990 through 2004 were extrapolated using the percentage changes in annual refined zinc production at secondary smelters in the United States as provided by USGS *Minerals Yearbook: Zinc* (USGS 1995 through 2005). The 3.70 metric tons CO₂/metric ton zinc emission factor was then applied to the Monaca facility's production levels to estimate CO₂ emissions for the facility. The Waelz kiln production emission factor was applied in this case rather than the EAF dust consumption emission factor since Horsehead's Monaca facility did not consume EAF dust.

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 Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC), 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 Horsehead Corporation (which is available from Horsehead's financial reports). Also, the EAF dust consumption for PIZO's facility for 2011 through 2013 was estimated by multiplying the average capacity utilization factor developed from Horsehead Corp. 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 and SDR's annual EAF dust consumption values (except SDR's EAF dust consumption for 2011 through 2013, which were obtained from SDR's recycling facility in Alabama).

Second, there is uncertainty associated with the emission factors used to estimate CO₂ 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 4-90. Zinc production CO₂ emissions were estimated to be between 0.8 and 1.2 MMT CO₂ 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 CO₂ Eq.

Table 4-90: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Zinc Production (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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 recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

4.22 Semiconductor Manufacture (IPCC Source Category 2E1)

The semiconductor industry uses multiple long-lived fluorinated greenhouse gases in plasma etching and plasma enhanced chemical vapor deposition (PECVD) processes to produce semiconductor products. The gases most commonly employed are trifluoromethane (HFC-23 or CHF₃), perfluoromethane (CF₄), perfluoroethane (C₂F₆), nitrogen trifluoride (NF₃), sulfur hexafluoride (SF₆), and nitrous oxide (N₂O), although other fluorinated compounds such as perfluoropropane (C₃F₈) and perfluorocyclobutane (c-C₄F₈) are also used. The exact combination of compounds is specific to the process employed.

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 atmosphere. 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 C₂F₆ is used in cleaning or etching, CF₄ is generated and emitted as a process 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).

For 2014, total GWP-weighted emissions of all fluorinated greenhouse gases and nitrous oxide from deposition, etching, and chamber cleaning processes in the U.S. semiconductor industry were estimated to be 4.7 MMT CO₂ Eq. Combined emissions of all greenhouse gases are presented in Table 4-91 and Table 4-92 below for years 1990, 2005 and the period 2010 to 2014. The rapid growth of this industry and the increasing complexity (growing number of layers)³⁸ of semiconductor products led to an increase in emissions of 153 percent between 1990 and 1999, when emissions peaked at 9.1 MMT CO₂ Eq. Emissions began to decline after 1999, declining by 48 percent between 1999 and 2014. Together, industrial growth, adoption of emissions reduction technologies, including but not limited to abatement technologies and shifts in gas usages resulted in a net increase in emissions of 32 percent between 1990 and 2014.

In 2010, the industry was still recovering from slowed economic activity which began in 2008. Between 2010 and 2011 fluorinated gas and N₂O emissions increased by 26 percent; reductions in emissions were then observed between 2011 and 2012, and 2012 and 2013 at 11 percent and 7 percent, respectively. Emissions increased between 2013 and 2014, by 13 percent. (As discussed below, this apparent increase between 2013 and 2014 may be an artifact of a change in the emission factors applied by facilities that report their emissions to EPA under the Greenhouse Gas Reporting Program (GHGRP)).

Table 4-91: PFC, HFC, SF₆, NF₃, and N₂O Emissions from Semiconductor Manufacture (MMT CO₂ Eq.)

Year	1990	2005	2010	2011	2012	2013	2014
CF ₄	0.8	1.1	1.1	1.4	1.3	1.2	1.5
C ₂ F ₆	2.0	2.0	1.4	1.8	1.6	1.4	1.4
C ₃ F ₈	+	0.1	0.1	0.2	0.1	0.1	0.1
C ₄ F ₈	0.0	0.1	+	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.2	0.2	0.2	0.2	0.3
SF ₆	0.5	0.7	0.4	0.4	0.4	0.4	0.7
NF ₃	+	0.5	0.6	0.7	0.6	0.6	0.5
Total F-GHGs	3.6	4.6	3.8	4.8	4.3	4.0	4.5
N ₂ O	+	0.1	0.1	0.2	0.2	0.2	0.2
Total	3.6	4.7	4.0	5.1	4.5	4.2	4.7

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 4-92: PFC, HFC, SF₆, NF₃, and N₂O Emissions from Semiconductor Manufacture (kt)

Year	1990	2005	2010	2011	2012	2013	2014
CF ₄	0.11	0.14	0.15	0.19	0.17	0.17	0.20
C ₂ F ₆	0.16	0.16	0.11	0.15	0.14	0.12	0.11
C ₃ F ₈	+	+	+	+	+	+	+
C ₄ F ₈	0.0	+	+	+	+	+	+
HFC-23	+	+	+	+	+	+	+
SF ₆	+	+	+	+	+	+	+
NF ₃	+	+	+	+	+	+	+
N ₂ O	0.12	0.41	0.49	0.80	0.66	0.61	0.69

+ Does not exceed 0.05 kt.

³⁸ 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.

Methodology

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, Partner reported emissions data received through the EPA's PFC³⁹ Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001),⁴⁰ 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 differs across the 1990 through 2014 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from semiconductor manufacturing were estimated using six distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 through 2012, and 2013 through 2014. Nitrous oxide emissions were estimated using four distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 through 2012, and 2013 through 2014.

1990 through 1994

From 1990 through 1994, Partnership data were unavailable and emissions were modeled using PEVM (Burton and Beizaie 2001).⁴¹ 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),⁴² and (2) product type (discrete, memory or logic).⁴³ 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

³⁹ In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

⁴⁰ 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.

⁴¹ 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.

⁴² 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).

⁴³ 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.

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. The emission factor is used to estimate world uncontrolled emissions using publicly-available data on world silicon consumption.

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).

To estimate N₂O emissions, it is assumed the proportion of N₂O 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 (Semiconductor Equipment and Materials Industry 2012 and 2013). Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period, the N₂O emissions were estimated using an emission factor that is applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N₂O 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 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 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.⁴⁴ Gas-specific emissions from non-Partners were estimated using linear interpolation of gas-specific emission distribution of 1999 (assumed same as total U.S. Industry in 1994) and 2011 (calculated from a subset of non-Partner facilities from GHGRP reported emissions data). Annual updates to PEVM reflect published figures for actual silicon

⁴⁴ 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.

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).^{45,46,47}

The N₂O 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.⁴⁸ 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 figure was assumed (SIA 2009).

In addition, publicly-available actual 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.

The N₂O 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,

⁴⁵ 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 2–3 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.

⁴⁶ 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.

⁴⁷ 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.

⁴⁸ 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.

the years after 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 CO₂ 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. In EPA's GHGRP, the population of non-Partner facilities also included manufacturers that use GaAs technology in addition to Si technology.⁴⁹ 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 populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions 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 N₂O emissions from CVD and other processes. The F-GHGs and N₂O 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 are not included in emission estimates (see Planned Improvements below).

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 N₂O and estimates of manufacturing activity. The new emission factors (in units of mass of CO₂ Eq./TMLA [MSI]) are based on the emissions reported by facilities under EPA's GHGRP and TMLA estimates for these facilities from the WFF (SEMI 2012 and SEMI 2013). In a refinement of the method used in prior years to estimate emissions for the non-Partner population, different emission factors were developed for different subpopulations of fabs, one for facilities that manufacture devices on Si wafers and one for facilities that manufacture on GaAs wafers. An analysis of the emission factors of reporting fabs showed that the characteristics that had the largest impacts on emission factors were the substrate (i.e., Si or GaAs) used at the fab, whether the fab contained R&D activities, and whether the fab reported using point-of-use fluorinated greenhouse gas abatement.⁵⁰ 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 (CF₄, C₂F₆, C₃F₈, C₄F₈, CHF₃, SF₆ and NF₃)⁵¹ were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO₂ Eq./MSI TMLA), and facility-reported N₂O emissions were regressed against the corresponding TMLA to estimate a N₂O emissions factor (CO₂ Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. To estimate emissions from fabs that are solely doing research and development (R&D) or are Pilot fabs (i.e., fabs that are excluded from subpart I reporting requirements), emission factors were estimated based on GHGRP reporting fabs containing R&D activities. EPA applied a scaling factor of 1.15 to the slope of the RTO model to estimate the emission factor applicable to the non-reporting fabs that are only R&D or Pilot fabs. This was done as R&D activities lead to use of more F-GHGs and N₂O for development of chips that are not counted towards the final estimated TMLA. Hence, it is assumed that the fabs with only R&D activities use 15 percent more F-GHGs and N₂O per TMLA.

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). Unlike the assumption for 2007 through 2010, all the facilities in the United States are assumed to utilize the same percent of the manufacturing capacity without distinguishing whether fabs have R&D activities or produce discrete products. This was done due to the unavailability of the data disaggregated into different fab, or manufacturing, types.

Non-reporting fabs were then broken out into similar subpopulations. Information on the technology and R&D activities of non-reporting fabs was available through the WFF. Information on the use of point-of-use abatement

⁴⁹ GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

⁵⁰ For the non-reporting segment of the industry using GaAs technology, emissions were estimated only for those fabs that manufactured the same products as manufactured by reporters. The products manufactured were categorized as discrete (emissions did not scale up with decreasing feature size).

⁵¹ 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.

by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement. 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 11, and 10 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.

The methodology used for this time period included emissions from facilities employing Si- and GaAs-using technologies. The use of GaAs technology became evident via analysis of GHGRP emissions and WFF data. However, no adjustment of pre-2011 emissions was made because (1) the use of these technologies appears relatively new, (2) in the aggregate these emissions make a relatively small contribution to total industry emissions (i.e., 3 percent in 2014), and (3) it would require a large effort to retroactively adjust pre-2011 emissions.

2013 through 2014

For the years 2013 through 2014, as for 2011 and 2012, F-GHG and N₂O 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, because WFF-derived activity data was not available for these years, an updated methodology to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP was used. 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 first estimated this proportion for both N₂O and F-GHGs for 2011 and 2012, resulting in one proportion for F-GHGs and one for N₂O, and then applied the average of these years' proportions 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 respectively. Again, a calculation of emissions from the use of heat transfer fluids was not included in this methodology.

Data Sources

GHGRP reporters, which consist of EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2b Method in the *2006 IPCC Guidelines*, this method uses different emission and by-product generation factors for different F-GHGs and process types, but it goes beyond the Tier 2b Method by requiring use of updated factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ thermal, and remote plasma). GHGRP-reporting facilities are estimated to have accounted for about 90 percent of F-GHG emissions and 95 percent of N₂O emissions from U.S. semiconductor manufacturing between 2011 and 2014. Historically, partners estimated and reported their emissions using a range of methods documented with varying completeness and consistency. 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) (e.g., Semiconductor Materials and Equipment Industry, 2013). 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 through 2014 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011 through 2014).

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:

$$\text{Total Emissions } (E_T) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F-GHG}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F-GHG}) + \text{GHGRP Reported N}_2\text{O Emissions } (E_{R,N_2O}) + \text{Non-Reporters' Estimated N}_2\text{O Emissions } (E_{NR,N_2O})$$

where E_R and E_{NR} denote totals for the indicated subcategories of emissions for F-GHG and N₂O, respectively.

The uncertainty in E_T presented in Table 4-93 below results from the convolution of four distributions of emissions, each reflecting separate estimates of possible values of $E_{R,F-GHG}$, E_{R,N_2O} , $E_{NR,F-GHG}$, and E_{NR,N_2O} . 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 $E_{R,F-GHG}$, 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).⁵² 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 C₃F₈ to ± 10 percent for CF₄. For the corresponding 300 mm industry segment, estimates of the 95 percent CI ranged from ± 36 percent for C₄F₈ to ± 16 percent for CF₄. These gas and wafer-specific uncertainty estimates are applied to the total emissions of 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 CF₄ to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C₄F₈, NF₃, and SF₆. 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.

⁵² 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.

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 N₂O consumed and the N₂O 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 N₂O consumed was assumed to be 20 percent.

Consumption of N₂O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N₂O 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 N₂O 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 each of the GHGRP reporting, N₂O-emitting facilities. The uncertainty for the total reported N₂O emissions was then estimated by combining the uncertainties of each of the 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 proportion of total emissions attributed to non-reporters for 2011 and 2012, which are subsequently dependent on the emissions factors for each non-reporting sub-category and the corresponding estimates of TMLA for the years 2011 and 2012.

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. For production fabs and for facilities that manufacture discrete devices, the most probable utilization is assumed to be 79 percent for 2011 and 65 percent for 2012, with the highest and lowest utilization assumed to be 84 percent for 2011 and 70 percent for 2012, and 62 percent for 2011 and 51 percent for 2012, respectively. The most probable values for utilization for R&D facilities are assumed to be 79 percent for 2011 and 65 percent for 2012, with the highest utilization also at 79 percent for 2011 and 65 percent for 2012, and the lowest utilization at 40 percent for 2011 and 33 percent for 2012. 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 for both 2011 and 2012.

The uncertainty around the emission factors for each non-reporting category of facilities (for both 2011 and 2012) is dependent on the uncertainty of the total emissions (MMT CO₂ Eq. units) and the TMLA of each reporting facility in that category. For each subpopulation of reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emissions 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.

For simplicity, the results of the Monte Carlo simulations on the bounds of the gas- and wafer size-specific emissions as well as the TMLA and emission factors are assumed to be normally distributed and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The departures from normality were observed to be small.

The final step in estimating the uncertainty in emissions of non-reporting facilities is convolving the distribution of emission factors with the distribution of TMLA individually for 2011 and 2012, along with the distributions of GHGRP-reported emissions for 2011 and 2012 to estimate the uncertainty around the proportion of total emissions attributed to non-reporters for 2011 and 2012 using Monte Carlo simulation.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-93, 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 N₂O emissions from semiconductor manufacturing were estimated to be between 4.5 and 5.0 MMT CO₂ Eq. at a 95 percent confidence level. This range represents 6 percent below to 6 percent above the 2014 emission estimate of 4.7 MMT CO₂ Eq. 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 4-93: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF₆, NF₃ and N₂O Emissions from Semiconductor Manufacture (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a (MMT CO ₂ Eq.) (%)			
			Lower Bound ^b	Upper Bound ^b	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, SF ₆ , NF ₃ , and N ₂ O	4.7	4.5	5.0	-6%	6%

^a Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

^b Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

The emissions reported under EPA's GHGRP for 2014, which are included in the overall emissions estimated for 2014, were based on an updated set of default emission factors. This may have affected the trend seen between 2013 and 2014 (a 13-percent increase), which reversed the trend seen between 2011 and 2013. As discussed in the Planned Improvements section, EPA is considering further analysis to determine how much, if any, of the 2013-2014 trend may be attributable to the updated factors.

Recalculations Discussion

Emissions from 2011 through 2013 were updated to reflect updated emissions reporting in EPA's GHGRP. Further, gas-process specific non-reporter emission factors were updated to reflect the historical changes in GHGRP data as well as updated manufacturing utilizations.

Methodological recalculations were applied to the entire time series to ensure time series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above. From 2000 through 2010, estimates increased slightly due to updated emission factors for 2011 resulting from a new source of utilization data (U.S. Census data) and updated GHGRP data. This has implications for the time series adjustment for 2000 through 2010 (i.e., the Partnership era). Interpolation is used to linearly decrease the non-partner population EF over time (2000 through 2010).

Planned Improvements

This Inventory contains estimates of seven fluorinated gases for semiconductor manufacturing and N₂O. However, other fluorinated gases (e.g., C₅F₈) are used in relatively smaller amounts. Previously, emissions data for these other fluorinated gases was not reported through the EPA Partnership. Through EPA's GHGRP, these data, as well as heat transfer fluid emission data, are available. Therefore, a point of consideration for future Inventory reports is the inclusion of other fluorinated gases, and emissions from heat transfer fluid (HTF) loss to the atmosphere.

Fluorinated heat transfer fluids, of which some are liquid perfluorinated compounds, are used for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Evaporation of these fluids is a source of fluorinated emissions (EPA 2006). The GHGRP-reported HTF emissions along with WFF database could be used to develop emission factors for identified subpopulations. Further research needs to be done to determine if the same subpopulations identified in developing new emission factors for F-GHGs are applicable or new subpopulations have to be studied as HTFs are used primarily by manufacturers of wafer size 300 mm and above.

Along with more emissions information for semiconductor manufacturing, EPA's GHGRP requires the reporting of emissions from other types of electronics manufacturing, including micro-electro-mechanical systems, flat panel displays, and photovoltaic cells. There currently are no flat panel displays, and photovoltaic cell manufacturing

facilities that are reporting to EPA's GHGRP, and five reporting MEMs manufacturers. The MEMs manufacturers also report emissions from semiconductor manufacturing and do not distinguish between these two types of manufacturing in their report; thus, emissions from MEMs manufacturers are included in the totals here. Emissions from manufacturing of flat panel displays and photovoltaic cells may be included in future Inventory reports; however, estimation methodologies would need to be developed.

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.

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.

Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. EPA is planning to investigate whether and how much this change may have affected the trend seen in estimated emissions between 2013 and 2014.

4.23 Substitution of Ozone Depleting Substances (IPCC 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 1990.⁵³ 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 4-94 and Table 4-95.

Table 4-94: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO₂ Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
HFC-23	+	+	+	+	+	+	+
HFC-32	+	0.3	2.6	3.4	4.4	5.4	6.4
HFC-125	+	9.5	31.4	37.2	43.6	49.9	55.9
HFC-134a	+	73.3	77.5	72.5	67.8	62.8	60.8
HFC-143a	+	9.4	20.3	22.5	24.4	26.0	27.2
HFC-236fa	+	1.2	1.4	1.4	1.5	1.5	1.4
CF ₄	+	+	+	+	+	+	+
Others ^a	0.3	5.9	7.8	8.2	8.6	9.0	9.4
Total	0.3	99.7	141.2	145.3	150.2	154.6	161.2

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HFO-1234yf, C₄F₁₀, 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 C₆F₁₄.

⁵³ [42 U.S.C § 7671, CAA Title VI]

Note: Totals may not sum due to independent rounding.

Table 4-95: Emissions of HFCs and PFCs from ODS Substitution (Metric Tons)

Gas	1990	2005	2010	2011	2012	2013	2014
HFC-23	+	1	2	2	2	2	3
HFC-32	+	511	3,915	5,032	6,479	7,985	9,475
HFC-125	+	2,701	8,983	10,626	12,445	14,259	15,974
HFC-134a	+	51,293	54,203	50,720	47,388	43,900	42,491
HFC-143a	+	2,108	4,548	5,034	5,451	5,813	6,088
HFC-236fa	+	125	146	147	148	151	148
CF ₄	+	2	3	4	4	4	4
Others ^a	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.

M (Mixture of Gases)

^a Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-43-10mee, HFO-1234yf, C₄F₁₀, 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—and HFC-134a in refrigeration end-uses. 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.⁵⁴ 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 161.2 MMT CO₂ Eq. in 2014. 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 4-96 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2014. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2014 include refrigeration and air-conditioning (139.2 MMT CO₂ Eq., or approximately 86 percent), aerosols (10.8 MMT CO₂ Eq., or approximately 7 percent), and foams (8.0 MMT CO₂ Eq., or approximately 5 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (40.9 MMT CO₂ Eq.), followed by refrigerated retail food and refrigerated transport. Each of the end-use sectors is described in more detail below.

Table 4-96: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO₂ Eq.) by Sector

Sector	1990	2005	2010	2011	2012	2013	2014
Refrigeration/Air Conditioning	+	87.8	122.8	125.9	130.0	133.6	139.2
Aerosols	0.3	7.6	9.7	10.1	10.3	10.5	10.8
Foams	+	2.1	5.9	6.4	6.9	7.4	8.0
Solvents	+	1.7	1.7	1.7	1.7	1.8	1.8
Fire Protection	+	0.7	1.1	1.2	1.3	1.3	1.4
Total	0.3	99.7	141.2	145.3	150.2	154.6	161.2

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

⁵⁴ 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 is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,⁵⁵ R-404A, and R-507A.⁵⁶ Low-GWP options such as HFO-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) in retail food refrigeration, are also being used. These refrigerants are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at 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). Many 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 has started to use 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 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 carbon dioxide (CO₂), methylene chloride, 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 polyurethane 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 CO₂ 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 -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 (CCl₄) 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 selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent,

⁵⁵ R-410A contains HFC-32 and HFC-125.

⁵⁶ R-507A, also called R-507, contains HFC-125 and HFC-143a.

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. As fire protection equipment is tested or deployed, emissions of these 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 more than 60 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 Vintaging Model estimates emissions from 66 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 21 end-uses, comprising over 95 percent of the total emissions, and 6 other end-uses. These 27 end-uses comprise 97 percent of the total emissions, equivalent to 156.4 MMT CO₂ Eq. In an effort to improve the uncertainty analysis, additional end-uses are added annually, with the intention that over time uncertainty for all emissions from the Vintaging Model will be fully characterized. Any end-uses included in previous years’ uncertainty analysis were included in the current uncertainty analysis, whether or not those end-uses were included in the top 95 percent of emissions from ODS substitutes.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex “vintage” 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 emission factors for residential unitary air-conditioners, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-97. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 154.2 and 172.5 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 1.4 percent below to 10.3 percent above the emission estimate of 156.4 MMT CO₂ Eq., which comprises 97 percent of total emissions.

Table 4-97: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO₂ Eq. and Percent)

Source	Gases	2014 Emission Estimate (MMT CO ₂ Eq.) ^a	Uncertainty Range Relative to Emission Estimate ^b (MMT CO ₂ Eq.) (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	156.4	154.2	172.5	-1.4%	+10.3%

^a 2014 emission estimates and the uncertainty range presented in this table correspond to selected end-uses within the aerosols, foams, solvents, fire extinguishing agents, and refrigerants sectors that comprise 97 percent of total emissions, but not for other remaining categories. Therefore, because the uncertainty associated with emissions from “other” ODS substitutes was not estimated, they were excluded in the uncertainty estimates reported in this table.

^b 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Comparison of Reported Consumption to Modeled Consumption of HFCs

Data from EPA’s Greenhouse Gas Reporting Program (GHGRP) was also used to perform quality control on the modeled emissions from this source category. To do so, reported consumption patterns demonstrated through GHGRP Subpart OO: Suppliers of Industrial Greenhouse Gases reported data 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 United States.⁵⁷ 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.

Reported Net Supply (GHGRP Top-Down Estimate)

Under EPA’s GHGRP, suppliers (i.e., producers, importers, and exporters) of HFCs began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010). For the first time in 2015, bulk consumption data for aggregated HFCs 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 (2010 through 2014). The data include all 19 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.

⁵⁷ Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

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.⁵⁸ It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (usually 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 ten 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, and HFC-43-10mee. For the purposes of this comparison, only nine 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.

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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 4-98 compares the net supply of saturated HFCs (excluding HFC-23) in million metric tons of CO₂ Eq. as determined from Subpart OO of EPA's GHGRP for the years 2010 through 2014 and the chemical demand as calculated by the Vintaging Model for the same time series.

Table 4-98: U.S. HFC Consumption (MMT CO₂ Eq.)

	2010	2011	2012	2013	2014
Reported Net Supply (GHGRP)	235	241	227	278	254
Modeled Supply (Vintaging Model)	256	256	273	278	282
Percent Difference	9%	6%	20%	0%	11%

As shown, the estimates from the Vintaging Model are higher than the GHGRP estimates by an average of 9 percent across the time series (i.e., 2010 through 2014). Potential reasons for these differences include:

- The Vintaging Model includes fewer 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 CO₂ Eq. amounts in the EPA's 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

⁵⁸ 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.

comparing data. Because the EPA's GHGRP data generally increases over time (although some year-to-year variations exist) and the Vintaging Model estimates also increase, EPA would expect the modeled estimates to be slightly higher than the corresponding GHGRP data due to this temporal effect.

- Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of 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 CO₂ 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.
- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical stockpiles; in other years, the opposite may hold true. Averaging imports and exports 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 4-99, the percent difference between the consumption estimates decreases compared to the 2012-only estimates.

Table 4-99: Averaged U.S. HFC Demand (MMT CO₂ Eq.)

	2010-2011 Avg.	2011-2012 Avg.	2012-2013 Avg.	2013-2014 Avg.
Reported Net Supply (GHGRP)	238	234	253	266
Modeled Demand (Vintaging Model)	256	264	275	280
Percent Difference	7%	13%	9%	5%

- 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, actual consumption for specific chemicals may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, or destroyed than produced or 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 data and bringing those totals closer to the Vintaging Model estimates.
- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, 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. Therefore, the GHGRP data may include 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. 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. Reporting under the EPA's GHGRP Subpart QQ: Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged Equipment or Closed-Cell Foams could be analyzed in the future to investigate this issue further.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence higher than EPA's 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 that 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 2014 emissions from that non-modeled source (0.1 MMT CO₂ Eq.) are much smaller than those for the ODS substitute sector (161.2 MMT CO₂ Eq).

Using a Tier 2 bottom-up modeling methodology to estimate emissions requires assumptions and expert judgement. 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 in some of the years. 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, reviews of the large retail food and refrigerated transport end-uses resulted in revisions to the Vintaging Model since the previous Inventory report. In addition, a vending machine end-use was added to the Vintaging Model since the previous Inventory. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014.

For the large retail food end-use, assumptions regarding new installations by system type and refrigerant transitions were revised based on a review of data collected by EPA's GreenChill Partnership and the California Air Resources Board's Refrigerant Management Program. Based on a literature review of technical reports and relevant datasets, the refrigerated transport end-use was updated from an aggregate end-use that covered all the various refrigerated transport modes through average assumptions of charge size, leak rates, stock, and lifetimes to separate end-uses by mode, including road transport, intermodal containers, merchant fishing, reefer ships, and vintage and modern rail. The vending machine end-use was added based on a review of technical reports and sales data. Combined, these assumption changes and additions decreased CO₂-equivalent greenhouse gas emissions on average by 5 percent between 1990 and 2014.

4.24 Electrical Transmission and Distribution (IPCC Source Category 2G1)

The largest use of sulfur hexafluoride (SF₆), 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. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF₆ 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 SF₆ from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 5.6 MMT CO₂ Eq. (0.2 kt) in 2014. This quantity represents a 78 percent decrease from the estimate for 1990 (see Table 4-100 and Table 4-101). There are two potential causes for this decrease: (1) a sharp increase in the price of SF₆ during the 1990s and (2) a growing awareness of the magnitude and environmental impact of SF₆ emissions through programs such as EPA's voluntary SF₆ Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's Greenhouse Gas Reporting Program (GHGRP). Utilities participating in the Partnership have lowered their emission factor (kg SF₆ emitted per kg of nameplate capacity) by more than 80 percent since the Partnership began in 1999. Sulfur hexafluoride emissions reported by electric power systems to EPA's GHGRP have also decreased significantly since 2011, 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).

Table 4-100: SF₆ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO₂ Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	25.1	0.3	25.4
2005	9.8	0.8	10.6
2010	6.2	0.9	7.0
2011	5.7	1.1	6.8
2012	4.5	1.1	5.6
2013	4.2	1.2	5.4
2014	4.6	1.0	5.6

Note: Totals may not sum due to independent rounding.

Table 4-101: SF₆ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	Emissions
1990	1.1
2005	0.5
2010	0.3
2011	0.3
2012	0.2
2013	0.2
2014	0.2

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 SF₆ Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF₆ emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF₆ 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 SF₆ sales were 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* (IPCC 2006).⁵⁹ (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the

⁵⁹ 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 SF₆ during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

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.)

$$\text{Emissions (kilograms SF}_6\text{)} = \text{SF}_6 \text{ purchased to refill existing equipment (kilograms)} + \\ \text{nameplate capacity of retiring equipment (kilograms)}^{60}$$

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 SF₆ 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 SF₆ 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 SF₆ 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 SF₆ 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 SF₆ from electric power systems in 1999 (estimated to be 14.3 MMT CO₂ Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF₆ in storage containers. When SF₆ prices rise, utilities are likely to deplete internal inventories before purchasing new SF₆ at the higher price, in which case SF₆ sales will fall more quickly than emissions. On the other hand, when SF₆ prices fall, utilities are likely to purchase more SF₆ to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF₆ 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. Sulfur hexafluoride production in these countries is not included in the RAND survey and is not accounted for in any other manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty and Time-Series Consistency section below).

1999 through 2014 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2014 were estimated based on: (1) reporting from utilities participating in EPA's SF₆ Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by the 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, and 2013 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013), 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 2014, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 43 percent and 48 percent 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

⁶⁰ Nameplate capacity is defined as the amount of SF₆ within fully charged electrical equipment.

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 2014, approximately 0.2 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 92 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2014 data accounted for approximately 8 percent of the total emissions attributed to Partner utilities.⁶¹

GHGRP-Only Reporters

EPA's GHGRP requires users of SF₆ in electric power systems to report emissions if the facility has a total SF₆ nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF₆ emissions of approximately 25,000 metric tons of CO₂ equivalent at the historical emission rate reported under the Partnership.) As under the Partnership, electric power systems that report their SF₆ 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. 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 24 percent of U.S. transmission miles and 26 percent of estimated U.S. emissions from electric power system in 2014.⁶²

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.⁶³ Two equations were developed, one for "non-large" and one for "large" utilities (i.e., with fewer or greater than 10,000 transmission miles, respectively). The distinction between utility sizes was made because the regression analysis showed that the relationship between emissions and transmission miles differed for non-large and large transmission networks. As noted above, non-Partner emissions were reported to 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 for both large and non-large utilities. The availability of non-Partner emissions estimates allowed the regression analysis to be modified for both large and non-large groups. Specifically, emissions were estimated for Non-Reporters as follows:

⁶¹ It should be noted that data reported through EPA's GHGRP must go through a verification process; only data verified as of September 1, 2015 could be used in the emission estimates for 2014. For Partners whose GHGRP data was not yet verified, emissions were extrapolated based upon historical Partner-specific transmission mile growth rates, and those Partners are included in the 'non-reporting Partners' category.

For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted. In addition, EPA manually reviewed the reported data and compared each facility's reported transmission miles with the corresponding quantity in the UDI 2013 database (UDI 2013). In the first year of GHGRP reporting, EPA followed up with reporters where the discrepancy between the reported miles and the miles published by UDI was greater than 10 percent, with a goal to improve data quality. Only GHGRP data verified as of September 1, 2015 was included in the emission estimates for 2011, 2012, 2013, and 2014.

⁶² Also, GHGRP-reported emissions from 17 facilities that had one or fewer transmission miles were included in the emission estimates for 2011. Emissions from these facilities comprise approximately 1.2 percent of total reported and verified emissions. In 2012, 16 facilities had one or fewer transmission miles, comprising 1.4 percent of verified emissions and in 2013, 16 facilities had one or fewer transmission miles, comprising 3.2 percent of verified emissions. In 2014, there were 12 such facilities that comprised 0.5 percent of verified emissions. These facilities were not included in the development of the regression equations (discussed further below). EPA is continuing to investigate whether or not these emissions are already implicitly accounted for in the relationship between transmission miles and emissions, and whether to update the regression analysis to better capture emissions from non-reporters that may have zero transmission miles.

⁶³ In the United States, SF₆ is contained primarily in transmission equipment rated above 34.5 kV.

- 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 for both “non-large” and “large” utilities. Historical emissions from Non-Reporters for both “non-large” and “large” utilities were estimated by linearly interpolating between the 1999 regression coefficients (based on 1999 Partner data) and the 2011 regression coefficients.
- 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 and 2014 using Partner and GHGRP-Only Reporter data for 2013 and 2014.

- “Non-large” utilities (*less than 10,000 transmission miles*): The 2014 regression equation for “non-large” utilities was developed based on the emissions reported by a subset of 88 Partner utilities and GHGRP-Only utilities (representing approximately 51 percent of total U.S. transmission miles for utilities with fewer than 10,000 transmission miles). The regression equation for 2014 is:

$$\text{Emissions (kg)} = 0.26 \times \text{Transmission Miles}$$

- “Large” utilities (*more than 10,000 transmission miles*): The 2014 regression equation was developed based on the emissions reported by a subset of 21 Partners and GHGRP-only utilities (representing approximately 86 percent of total U.S. transmission miles for utilities with greater than 10,000 transmission miles). The regression equation for 2014 is:

$$\text{Emissions (kg)} = 0.22 \times \text{Transmission Miles}$$

Table 4-102 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for both large and non-large reporters for 1999 (the first year data was reported), and for 2011 through 2014 (the first three years with GHGRP reported data). The coefficient for non-large utilities increased between 2013 and 2014 and the coefficient for large utilities decreased slightly between 2013 and 2014.

Table 4-102: Transmission Mile Coverage and Regression Coefficients for Large and Non-Large Utilities

	Non-large					Large				
	1999	2011	2012	2013	2014	1999	2011	2012	2013	2014
Percentage of Miles Covered by Reporters	31	45	44	47	51	86	97	88	83	86
Regression Coefficient ^a	0.89	0.33	0.23	0.22	0.26	0.58	0.26	0.22	0.22	0.22

^a Regression coefficient is defined as emissions (in kg) divided by transmission miles.

Note: “Non-large” represents reporters with fewer than 10,000 transmission miles.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, and 2012 were obtained from the 2001, 2004, 2007, 2010, and 2013 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013). The U.S. transmission system grew by over 25,000 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. This growth rate grew to 3 percent from 2006 to 2009 as transmission miles increased by more than 59,000 miles. The annual growth rate for 2009 through 2012 was calculated to be 2.0 percent as transmission miles grew by approximately 43,000 during this time period.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2014 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF₆ 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 2014 Emissions from Manufacture of Electrical Equipment

The 1990 to 2013 emission estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF₆ provided with new equipment. The quantity of SF₆ 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; the quantities of SF₆ provided with new equipment for 2001 to 2014 were estimated using Partner reported data and the total industry SF₆ nameplate capacity estimate (196.4 MMT CO₂ Eq. in 2013). 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 2014 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF₆ provided with new equipment for the entire industry. 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).

Uncertainty and Time-Series Consistency

To estimate the uncertainty associated with emissions of SF₆ 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 SF₆ Emission Reduction Partnership include emissions from both reporting (through the Partnership or GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF₆ 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 4.7 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF₆ data was assumed to have an uncertainty of 20 percent.⁶⁴ Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 6.1 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2013 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) the quantity of SF₆ supplied with equipment by equipment manufacturers, which is projected from Partner provided nameplate capacity data and industry SF₆ nameplate capacity estimates, and (2) the manufacturers' SF₆ emissions rate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-103. Electrical Transmission and Distribution SF₆ emissions were estimated to be between 4.6 and 6.9 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 23 percent above the emission estimate of 5.6 MMT CO₂ Eq.

⁶⁴ 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 4-103: Approach 2 Quantitative Uncertainty Estimates for SF₆ Emissions from Electrical Transmission and Distribution (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission	Uncertainty Range Relative to 2014 Emission Estimate ^a			
		Estimate (MMT CO ₂ Eq.)	(MMT CO ₂ Eq.)	Lower Bound	Upper Bound	Lower Bound (%)
Electrical Transmission and Distribution	SF ₆	5.6	4.6	6.9	-17%	+23%

^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 SF₆ sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF₆ appears to reflect the trend in global emissions implied by changing SF₆ 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. SF₆ emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF₆ 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 SF₆ recycling equipment, stated that most U.S. utilities began recycling rather than venting SF₆ 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 recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Recalculations Discussion

The historical emissions estimated for this source category have undergone some minor revisions. SF₆ emission estimates for the period 1990 through 2013 were updated relative to the previous report based on revisions to interpolated and extrapolated non-reported Partner data.⁶⁵ The regression coefficients to estimate emissions from non-reporting utilities were adjusted between the years 2011 and 2013 after correcting a spreadsheet error, and as a result, there were minor changes to the emissions from non-reporting utilities. Additionally, correction of a different spreadsheet error led to updated leak rates and OEM growth rates, which are used to calculate OEM emissions. These leak rates are used to estimate the nameplate capacity of non-reporters during these years, and are interpolated back through 1999 to calculate Non-Reporter nameplate capacity over the entire time series.⁶⁶

As a result of the recalculations, SF₆ emissions from electrical transmission and distribution increased by 6 percent for 2013 relative to the previous report. On average, the change in SF₆ emission estimates for the entire time series is approximately 0.1 percent per year.

Planned Improvements

EPA is exploring the use of OEM data that is reported under EPA's GHGRP to use for future Inventory reports instead of estimating those emissions based on elements reported by utilities to the GHGRP and Partner data.

⁶⁵ The earlier year estimates within the time series (i.e., 1990-1998) were updated based on revisions to the 1999 U.S. emission estimate because emissions for 1990-1998 are estimated by multiplying a series of annual factors by the estimated U.S. emissions of SF₆ from electric power systems in 1999 (see Methodology section).

⁶⁶ Nameplate capacity estimates affect sector emissions because OEM emission estimation is calculated using total industry nameplate capacity.

Specifically, using the GHGRP-reported OEM emissions and the estimated nameplate capacity increase estimated for users of electrical equipment (available in the existing methodology), a leak rate would be calculated. This approach would require estimating the portion of industry not reporting to EPA's GHGRP program, which would require market research. Once a new leak rate is established, leak rates could be interpolated for years between 2000 (at 10 percent) and 2011. 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.⁶⁷

4.25 Nitrous Oxide from Product Uses (IPCC 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 2014). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as 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 2014 was approximately 15 kt (see Table 4-104).

Table 4-104: N_2O Production (kt)

Year	kt
1990	16
2005	15
2010	15
2011	15
2012	15
2013	15
2014	15

Nitrous oxide emissions were 4.2 MMT CO₂ Eq. (14 kt N_2O) in 2014 (see Table 4-105). 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).

⁶⁷ See <http://www.ipcc-nngip.iges.or.jp/meeting/pdffiles/1008_Model_and_Facility_Level_Report.pdf>.

Table 4-105: N₂O Emissions from N₂O Product Usage (MMT CO₂ Eq. and kt)

Year	MMT CO ₂ Eq.	kt
1990	4.2	14
2005	4.2	14
2010	4.2	14
2011	4.2	14
2012	4.2	14
2013	4.2	14
2014	4.2	14

Methodology

Emissions from N₂O product uses were estimated using the following equation:

$$E_{pu} = \sum_a (P \times S_a \times ER_a)$$

where,

E _{pu}	=	N ₂ O emissions from product uses, metric tons
P	=	Total U.S. production of N ₂ O, metric tons
a	=	specific application
S _a	=	Share of N ₂ O usage by application <i>a</i>
ER _a	=	Emission rate for application <i>a</i> , percent

The share of total quantity of N₂O usage by end-use represents the share of national N₂O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2014, the medical/dental industry used an estimated 86.5 percent of total N₂O produced, followed by food processing propellants at 6.5 percent. All other categories combined used the remainder of the N₂O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N₂O usage in the production of sodium azide has 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 N₂O 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). The N₂O was allocated across the following categories: medical applications, food processing propellant, and sodium azide production (pre-1996). A usage emissions rate was then applied for each sector to estimate the amount of N₂O emitted.

Only the medical/dental and food propellant subcategories were estimated to release emissions into the atmosphere, and therefore these subcategories were the only usage subcategories with emission rates. For the medical/dental subcategory, due to the poor solubility of N₂O in blood and other tissues, none of the N₂O 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 N₂O used as a propellant in pressurized and aerosol food products, none of the N₂O is reacted during the process and all of the N₂O 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 N₂O is consumed/reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N₂O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (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 2002). In particular, for 1996, Heydorn (1997) estimates N₂O 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 N₂O emissions for years 1993 through 2001.

(Tupman 2003). The 2002 and 2003 N₂O 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 N₂O production to range between 13.6 and 15.9 thousand metric tons. Due to the unavailability of data, production estimates for years 2004 through 2014 were held constant at the 2003 value.

The 1996 share of the total quantity of N₂O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). The 1990 through 1995 share of total quantity of N₂O 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 N₂O usage by sector was obtained from communication with a N₂O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N₂O usage by sector was obtained from CGA (2002, 2003). Due to the unavailability of data, the share of total quantity of N₂O usage data for years 2004 through 2014 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* report (Heydorn 1997), and confirmed by a N₂O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N₂O industry expert (Tupman 2002). 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 2014 N₂O emission estimate from N₂O product usage was calculated using the *2006 IPCC Guidelines* (2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N₂O 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 4-106. Nitrous oxide emissions from N₂O product usage were estimated to be between 3.2 and 5.2 MMT CO₂ 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 CO₂ Eq.

Table 4-106: Approach 2 Quantitative Uncertainty Estimates for N₂O Emissions from N₂O Product Usage (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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 ₂ O from Product Uses	N ₂ O	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 recalculations were applied to the entire time series to ensure consistency in emissions from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

Planned Improvements

Pending resources, planned improvements include a continued evaluation of alternative production statistics for cross verification, a reassessment of N₂O product use subcategories to accurately represent trends, investigation of production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N₂O. Additionally, planned improvements include considering imports and exports of N₂O for product uses. Finally, for future Inventories EPA will examine data from EPA's Greenhouse Gas Reporting Program (GHGRP) to improve the emission estimates for the N₂O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing confidential business information 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.

4.26 Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various ozone precursors (i.e., indirect greenhouse gases). As some of industrial applications also employ thermal incineration as a control technology, combustion byproducts, such as carbon monoxide (CO) and nitrogen oxides (NO_x), are also reported with this source category. Non- CH_4 volatile organic compounds (NMVOCs), commonly referred to as “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 2014 are reported in Table 4-107.

Table 4-107: NO_x , CO, and NMVOC Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
NO_x	592	572	472	452	452	452	452
Industrial Processes							
Other Industrial Processes	343	437	339	320	320	320	320
Metals Processing	88	60	67	64	64	64	64
Chemical and Allied Product Manufacturing	152	55	48	47	47	47	47
Storage and Transport	3	15	15	18	18	18	18
Miscellaneous ^a	5	2	2	3	3	3	3
Product Use							
Surface Coating	1	3	2	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 ^b	+	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	1,280	1,229	1,229	1,229	1,229
Industrial Processes							
Metals Processing	2,395	752	717	695	695	695	695
Other Industrial Processes	487	484	333	306	306	306	306
Chemical and Allied Product Manufacturing	1,073	189	157	152	152	152	152
Miscellaneous ^a	101	32	48	51	51	51	51
Storage and Transport	69	97	22	25	25	25	24
Product Use							
Surface Coating	+	2	3	2	2	2	2
Other Industrial Processes ^b	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	4,133	3,929	3,929	3,929	3,928
Industrial Processes							
Storage and Transport	1,352	1,308	992	947	947	947	946
Other Industrial Processes	364	414	308	298	298	298	298
Chemical and Allied Product Manufacturing	575	213	77	76	76	76	75
Metals Processing	111	45	32	31	31	31	31
Miscellaneous ^a	20	17	26	27	27	27	27
Product Use							
Surface Coating	2,289	1,578	1,105	1,045	1,045	1,045	1,045
Non-Industrial Processes ^c	1,724	1,446	1,013	957	957	957	957
Degreasing	675	280	196	186	186	186	186
Dry Cleaning	195	230	161	152	152	152	152
Graphic Arts	249	194	136	128	128	128	128
Other Industrial Processes ^b	85	88	61	58	58	58	58
Other	+	36	25	24	24	24	24

+ Does not exceed 0.5 kt

NA (Not Available)

^a 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.

^b Includes rubber and plastics manufacturing, and other miscellaneous applications.

^c Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2014 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Data were collected for emissions of CO, NO_x, volatile organic compounds (VOCs), and sulfur dioxide (SO₂) from metals processing, chemical manufacturing, other industrial processes, transport and storage, and miscellaneous sources. Emission estimates for 2013 for non-electric generating unit (EGU) and non-mobile sources are held constant from 2011 in EPA (2015). 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

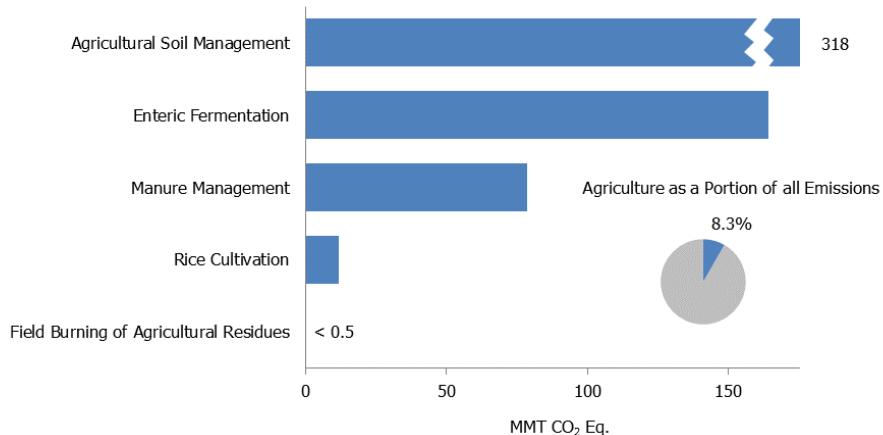
Uncertainties in these estimates are partly due to the accuracy of the emission factors and activity data used. A quantitative uncertainty analysis was not performed.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon-dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 5-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as liming and conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 5-1: 2014 Agriculture Chapter Greenhouse Gas Emission Sources (MMT CO_2 Eq.)



In 2014, the Agriculture sector was responsible for emissions of 573.6 MMT CO_2 Eq.¹ or 8.3 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represent 22.5 percent and 8.4 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4 . Rice cultivation and field burning of agricultural residues were minor sources of CH_4 . Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 78.9 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

¹ Following the revised 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.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2014, CH₄ emissions from agricultural activities increased by 10.7 percent, while N₂O emissions fluctuated from year to year, but overall increased by 5.9 percent.

Table 5-1: Emissions from Agriculture (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	214.7	238.4	244.4	242.5	242.6	239.0	237.7
Enteric Fermentation	164.2	168.9	171.3	168.9	166.7	165.5	164.3
Manure Management	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Rice Cultivation	13.1	13.0	11.9	11.8	11.9	11.9	11.9
Field Burning of Agricultural Residues	0.2	0.2	0.3	0.3	0.3	0.3	0.3
N₂O	317.4	313.8	338.0	340.6	340.7	336.2	336.0
Agricultural Soil Management	303.3	297.2	320.7	323.1	323.1	318.6	318.4
Manure Management	14.0	16.5	17.2	17.4	17.5	17.5	17.5
Field Burning of Agricultural Residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	532.0	552.2	582.3	583.1	583.3	575.3	573.6

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	8,587	9,537	9,776	9,702	9,705	9,562	9,506
Enteric Fermentation	6,566	6,755	6,853	6,757	6,670	6,619	6,572
Manure Management	1,486	2,254	2,437	2,460	2,548	2,455	2,447
Rice Cultivation	525	521	474	474	476	477	476
Field Burning of Agricultural Residues	10	8	11	11	11	11	11
N₂O	1,065	1,053	1,134	1,143	1,143	1,128	1,127
Agricultural Soil Management	1,018	997	1,076	1,084	1,084	1,069	1,068
Manure Management	47	55	58	58	59	59	59
Field Burning of Agricultural Residues	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

5.1 Enteric Fermentation (IPCC 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 CH₄ as a byproduct, which can be exhaled or eructated by the animal. The amount of CH₄ produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH₄ 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 CH₄ emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH₄ emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit

significantly less CH₄ on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH₄ is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH₄ emissions. In general, lower feed quality and/or higher feed intake leads to higher CH₄ 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 CH₄ emissions in 2014 were 164.3 MMT CO₂ Eq. (6,572 kt). Beef cattle remain the largest contributor of CH₄ emissions from enteric fermentation, accounting for 71 percent in 2014. Emissions from dairy cattle in 2014 accounted for 26 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.

From 1990 to 2014, emissions from enteric fermentation have increased by 0.1 percent. While emissions generally follow trends in cattle populations, over the long term there are exceptions as population decreases have been coupled with production increases or minor decreases. For example, beef cattle emissions decreased 2.0 percent from 1990 to 2014, while beef cattle populations actually declined by 7 percent and beef production increased (USDA 2015), and while dairy emissions increased 6.5 percent over the entire time series, the population has declined by 5 percent and milk production increased 40 percent (USDA 2015). This trend indicates that while emission factors per head are increasing, emission factors per unit of product are going down. Generally, from 1990 to 1995 emissions from beef 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 populations underwent increases and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2008 to 2014 as populations again decreased. Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy 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). Dairy cattle emissions have continued to trend upward since 2007, in line with dairy 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 56 percent greater than they were in 1990, but their numbers have been declining by about 2 percent annually since 2007. Goat populations increased by about 20 percent through 2007 but have since dropped below 1990 numbers, while swine populations have increased 19 percent since 1990. The population of American bison more than tripled over the 1990 through 2014 time period, while mules and asses have more than quadrupled.

Table 5-3: CH₄ Emissions from Enteric Fermentation (MMT CO₂ Eq.)

Livestock Type	1990	2005	2010	2011	2012	2013	2014
Beef Cattle	119.1	125.2	124.6	121.8	119.1	118.0	116.7
Dairy Cattle	39.4	37.6	40.7	41.1	41.7	41.6	41.9
Swine	2.0	2.3	2.4	2.5	2.5	2.5	2.4
Horses	1.0	1.7	1.7	1.7	1.6	1.6	1.6
Sheep	2.3	1.2	1.1	1.1	1.1	1.1	1.0
Goats	0.3	0.4	0.4	0.3	0.3	0.3	0.3
American Bison	0.1	0.4	0.4	0.3	0.3	0.3	0.3
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	164.2	168.9	171.3	168.9	166.7	165.5	164.3

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH₄ Emissions from Enteric Fermentation (kt)

Livestock Type	1990	2005	2010	2011	2012	2013	2014
Beef Cattle	4,763	5,007	4,984	4,873	4,763	4,722	4,667
Dairy Cattle	1,574	1,503	1,627	1,645	1,670	1,664	1,677
Swine	81	92	97	98	100	98	96
Horses	40	70	68	67	65	64	62

Sheep	91	49	45	44	43	43	42
Goats	13	14	14	14	13	13	12
American Bison	4	17	15	14	13	13	12
Mules and Asses	1	2	3	3	3	3	3
Total	6,566	6,755	6,853	6,757	6,670	6,619	6,572

Note: Totals may not sum due to independent rounding.

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 CH₄ emissions from livestock in the United States. A more detailed methodology (i.e., Intergovernmental Panel on Climate Change [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 handled using a less detailed approach (i.e., IPCC Tier 1).

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 the U.S. Environmental Protection Agency (EPA) and used to estimate cattle CH₄ emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

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 2015).

Diet characteristics were estimated by region for dairy, foraging 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 CH₄ conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH₄) 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.² Base year Y_m values by region were estimated using Donovan (1999). 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 CH₄ 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 CH₄ 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 CH₄ 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.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH₄ emissions from livestock in the United States from 1990 through 2014. 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 sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA NASS (USDA 2015). Horse, goat and mule and ass population data were available for 1987, 1992, 1997, 2002, 2007, and 2012 (USDA 1992, 1997, 2015); the remaining years between 1990 and 2014 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 2014) and from the National Bison Association (1999) for 1997 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).

² Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

See Annex 3.10 for more detailed information on the methodology and data used to calculate CH₄ emissions from enteric fermentation.

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 report (i.e., 2003 submission to the UNFCCC). There have been no significant changes to the methodology since that time; consequently, these uncertainty estimates were directly applied to the 2014 emission estimates in this Inventory report.

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.

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 5-5. Based on this analysis, enteric fermentation CH₄ emissions in 2014 were estimated to be between 146.2 and 193.9 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2014 emission estimate of 164.3 MMT CO₂ Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH₄ 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.

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Enteric Fermentation (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	164.3	146.2	193.9	-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 2014 estimates.

^c The overall uncertainty calculated in 2003, and applied to the 2014 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 recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. 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.

Recalculations Discussion

For the current Inventory, differences can be seen in emission estimates for years prior to 2014 when compared against the same years in the previous Inventory—from 2008 through 2013 in particular. These recalculations were due to changes made to historical data and corrections made to erroneous formulas in the CEFM. No modifications were made to the methodology.

Revisions to input data include the following:

- The USDA published minor revisions in several categories that affected historical emissions estimated for cattle for 2008 and subsequent years, including the following:
 - Cattle populations for all animal types were revised for many states for 2009 and subsequent years;
 - Dairy cow milk production values were revised for several states for 2008 and subsequent years;
 - Beef cattle feedlot placement data were revised for 2008 and subsequent years;
 - Slaughter values were revised for 2008 and subsequent years;
 - Calf birth data were revised for 2010 and subsequent years; and
 - Cattle on feed data were revised for many states for 2009 and subsequent years.
- The USDA also revised population estimates for some categories of non-cattle animals, which affected historical emissions estimated for “other” livestock. Changes included:
 - Revised 2008 through 2012 populations for market and breeding swine in some states; and
 - Revised 2011 and 2012 populations of sheep for some states.

In addition to these changes in input data, there were transcription and formula cell reference errors in the CEFM calculations for the state-by-state estimates of cattle on feed. These errors, when corrected, affected emission estimates for 2009 and subsequent years for all stockers and feedlot cattle.

These recalculations had an insignificant impact on the overall emission estimates.

Planned Improvements

Continued research and regular updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. Future improvements for enteric fermentation could include some of the following options:

- 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 and beef cow lactation rates;
- Investigation of the availability of annual data for the DE, Y_m , and crude protein values of specific diet and feed components for foraging and feedlot animals;
- Further investigation on additional sources or methodologies for estimating DE for dairy, given the many challenges in characterizing dairy 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;
- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses);
- 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; and
- 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.

5.2 Manure Management (IPCC Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH₄ and N₂O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide emissions are produced through both direct and indirect pathways. Direct N₂O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the organic N in livestock dung and urine.³ There are two pathways for indirect N₂O emissions. The first is the result of the volatilization of N in manure (as NH₃ and NO_x) and the subsequent deposition of these gases and their products (NH₄⁺ and NO₃⁻) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure to the groundwater below, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

When livestock or poultry manure are 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 CH₄. 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 little or no CH₄. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH₄ produced because they influence the growth of the bacteria responsible for CH₄ formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH₄ production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH₄ produced. In general, the greater the energy content of the feed, the greater the potential for CH₄ 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.

The production of direct N₂O emissions from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N₂O emissions to occur, the manure must first be handled aerobically where ammonia (NH₃) or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to dinitrogen gas (N₂), with intermediate production of N₂O and nitric oxide (NO) (denitrification)

³ Direct and indirect N₂O 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.

(Groffman et al. 2000). 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 N₂O in the waste management system (WMS). Indirect N₂O emissions are produced when nitrogen is lost from the system through volatilization (as NH₃ or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH₃. 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 NH₃ 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 CH₄ emissions from manure management in 2014 were 61.2 MMT CO₂ Eq. (2,447 kt); in 1990, emissions were 37.2 MMT CO₂ Eq. (1,486 kt). This represents a 65 percent increase in emissions from 1990. Emissions increased on average by 1.0 MMT CO₂ Eq. (2.6 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 44 and 118 percent, respectively. From 2013 to 2014, there was a 0.3 percent decrease in total CH₄ emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

Although the majority of managed manure in the United States is handled as a solid, producing little CH₄, the general trend in manure management, particularly for dairy 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. Although national dairy animal populations have generally been decreasing since 1990, some states have seen increases in their dairy 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 and swine facilities has translated into an increasing use of liquid manure management systems, which have higher potential CH₄ emissions than dry systems. This significant shift in both the dairy and swine industries was accounted for by incorporating state and WMS-specific CH₄ conversion factor (MCF) values in combination with the 1992, 1997, 2002, and 2007 farm-size distribution data reported in the *Census of Agriculture* (USDA 2014a).

In 2014, total N₂O emissions from manure management were estimated to be 17.5 MMT CO₂ Eq. (59 kt); in 1990, emissions were 14.0 MMT CO₂ Eq. (47 kt). These values include both direct and indirect N₂O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N₂O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N₂O emissions showed a 25 percent increase from 1990 to 2014 and a 0.1 percent decrease from 2013 through 2014. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted.

Table 5-6 and Table 5-7 provide estimates of CH₄ and N₂O emissions from manure management by animal category.

Table 5-6: CH₄ and N₂O Emissions from Manure Management (MMT CO₂ Eq.)

Gas/Animal Type	1990	2005	2010	2011	2012	2013	2014
CH₄^a	37.2	56.3	60.9	61.5	63.7	61.4	61.2
Dairy Cattle	14.7	26.4	30.4	31.1	32.6	31.8	32.2
Beef Cattle	3.1	3.3	3.3	3.3	3.2	3.0	3.0
Swine	15.6	22.9	23.6	23.6	24.3	23.0	22.4
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Poultry	3.3	3.2	3.2	3.2	3.2	3.2	3.2
Horses	0.2	0.3	0.2	0.2	0.2	0.2	0.2
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O^b	14.0	16.5	17.2	17.4	17.5	17.5	17.5

Dairy Cattle	5.3	5.6	5.7	5.8	5.9	5.9	5.9
Beef Cattle	5.9	7.2	7.6	7.7	7.7	7.7	7.8
Swine	1.2	1.7	1.9	1.9	1.9	1.9	1.8
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Goats	+	+	+	+	+	+	+
Poultry	1.4	1.6	1.5	1.5	1.6	1.6	1.6
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
American Bison	NA						
Mules and Asses	+	+	+	+	+	+	+
Total	51.1	72.9	78.1	78.9	81.2	78.9	78.7

+ Does not exceed 0.05 MMT CO₂ Eq.

NA - Not available

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Includes both direct and indirect N₂O emissions.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N₂O emissions from managed systems.

Table 5-7: CH₄ and N₂O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2010	2011	2012	2013	2014
CH₄^a	1,486	2,254	2,437	2,460	2,548	2,455	2,447
Dairy Cattle	590	1,057	1,217	1,245	1,306	1,271	1,289
Beef Cattle	126	133	132	131	128	121	120
Swine	622	916	945	942	972	920	896
Sheep	7	3	3	3	3	3	3
Goats	1	1	1	1	1	1	1
Poultry	131	129	129	127	128	128	130
Horses	9	12	10	10	10	9	9
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N₂O^b	47	55	58	58	59	59	59
Dairy Cattle	18	19	19	19	20	20	20
Beef Cattle	20	24	25	26	26	26	26
Swine	4	6	6	6	6	6	6
Sheep	+	1	1	1	1	1	1
Goats	+	+	+	+	+	+	+
Poultry	5	5	5	5	5	5	5
Horses	+	+	+	+	+	+	+
American Bison	NA						
Mules and Asses	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

NA - Not available

^a Accounts for CH₄ reductions due to capture and destruction of CH₄ at facilities using anaerobic digesters.

^b Includes both direct and indirect N₂O emissions.

Notes: Totals may not sum due to independent rounding. American bison are maintained entirely on unmanaged WMS; there are no American bison N₂O emissions from managed systems.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH₄ and N₂O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH₄ and N₂O emissions from manure management. See Annex 3.11 for more detailed information on the methodology and data used to calculate CH₄ and N₂O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH₄ emissions:

- 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_o) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH₄ 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 2014 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 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, and 2012; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, and 2012; and American bison population for 2002, 2007 and 2012 were obtained from the *Census of Agriculture* (USDA 2014a). 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 Section 5.1.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2014a) and EPA (ERG 2000a; EPA 2002a and 2002b). 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.
- The maximum CH₄-producing capacity of the VS (B_o) 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 CH₄ capture and combustion were obtained from the EPA AgSTAR Program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003, 2006) and the

AgSTAR project database (EPA 2012). 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 CH₄ emissions (kg CH₄ per year) from each WMS. The amount of VS (kg per year) were multiplied by the maximum CH₄ producing capacity of the VS (B_o) (m³ CH₄ per kg VS), the MCF for that WMS (percent), and the density of CH₄ (kg CH₄ per m³ CH₄). The CH₄ emissions for each WMS, state, and animal type were summed to determine the total U.S. CH₄ emissions.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N₂O emissions:

- 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 N₂O emission factor (EF_{WMS});
- Indirect N₂O emission factor for volatilization (EF_{volatilization});
- Indirect N₂O emission factor for runoff and leaching (EF_{runoff/leach});
- Fraction of N loss from volatilization of NH₃ and NO_x (Frac_{gas}); and
- Fraction of N loss from runoff and leaching (Frac_{runoff/leach}).

N₂O 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 rates 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 rates were assumed to be the same as NOF bulls.⁴
- All N₂O emission factors (direct and indirect) were taken from IPCC (2006). These data are appropriate because they were developed using U.S. data.
- 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 N₂O 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)

⁴ The N₂O emissions from N excreted (Nex) by 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 N₂O emissions from unmanaged WMS are not included in the Manure Management category, there are no N₂O emissions from American bison included in the Manure Management category.

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 N₂O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N₂O direct emission factor for that WMS (EF_{WMS}, in kg N₂O-N per kg N) and the conversion factor of N₂O-N to N₂O. These emissions were summed over state, animal, and WMS to determine the total direct N₂O emissions (kg of N₂O per year).

Next, indirect N₂O emissions from volatilization (kg N₂O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization (Frac_{tas}) divided by 100, and the emission factor for volatilization (EF_{volatilization}, in kg N₂O per kg N), and the conversion factor of N₂O-N to N₂O. Indirect N₂O emissions from runoff and leaching (kg N₂O 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 N₂O per kg N), and the conversion factor of N₂O-N to N₂O. The indirect N₂O emissions from volatilization and runoff and leaching were summed to determine the total indirect N₂O emissions.

The direct and indirect N₂O emissions were summed to determine total N₂O emissions (kg N₂O per year).

Uncertainty and Time-Series Consistency

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory report (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH₄ and N₂O 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 CH₄ and N₂O 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. These uncertainty estimates were directly applied to the 2014 emission estimates as there have not been significant changes in the methodology since that time.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH₄ emissions in 2014 were estimated to be between 50.2 and 73.4 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2014 emission estimate of 61.2 MMT CO₂ Eq. At the 95 percent confidence level, N₂O emissions were estimated to be between 14.7 and 21.7 MMT CO₂ Eq. (or approximately 16 percent below and 24 percent above the actual 2014 emission estimate of 17.5 MMT CO₂ Eq.).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O (Direct and Indirect) Emissions from Manure Management (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	61.2	50.2	73.4	-18%	20%
Manure Management	N ₂ O	17.5	14.7	21.7	-16%	24%

^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 2014. Details on the emission trends through time are described in more detail in the Methodology section.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N₂O emissions from managed systems and CH₄ emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. 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.

Any updated data, including population, are validated by experts to ensure the changes are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_o, 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, the implied CH₄ emission factors for manure management (kg of CH₄ per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH₄ 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 and swine across the time series. This increase reflects the dairy and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH₄ emissions.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH₄ from Manure Management (kg/head/year)

Animal Type	IPCC Default CH ₄ Emission Factors (kg/head/year)	Implied CH ₄ Emission Factors (kg/head/year)						
		1990	2005	2010	2011	2012	2013	2014
Dairy Cattle	48-112	30.2	59.4	66.5	67.5	70.3	68.7	69.7
Beef Cattle	1-2	1.5	1.6	1.6	1.7	1.7	1.6	1.6
Swine	10-45	11.5	15.0	14.6	14.4	14.6	14.1	14.0
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	2.7	2.5	2.5
American Bison	NA	1.8	2.0	2.1	2.1	2.1	2.0	2.0
Mules and Asses	0.76-1.14	0.9	1.0	0.9	1.0	1.0	0.9	0.9

NA - Not Applicable

In addition, default IPCC (2006) emission factors for N₂O were compared to the U.S. Inventory implied N₂O emission factors. Default N₂O emission factors from the *2006 IPCC Guidelines* were used to estimate N₂O 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

The CEFM produces population, VS and Nex data for cattle, excepting calves, that are used in the manure management inventory. As a result, all changes to the CEFM described in Section 5.1 contributed to changes in the population, VS and Nex data used for calculating CH₄ and N₂O cattle emissions from manure management. In

addition, the manure management emission estimates included the following recalculations relative to the previous Inventory:

- State animal populations were updated to reflect updated USDA NASS datasets, which resulted in population changes for poultry in 2013, both beef and dairy calves from 2009 through 2013, sheep in 2011 and 2012, and swine from 2008 through 2013.
- Indirect N₂O emissions for daily spread were added, as they are not accounted for in the Agricultural Soil Management category. This inclusion increased indirect and total N₂O emissions for dairy cows and dairy heifers. Indirect N₂O emissions increased between 0.9 and 5.2 percent per year, while total N₂O emissions increased between 0.6 to 1.4 percent per year.

Planned Improvements

The uncertainty analysis for manure management will be updated in future Inventories to more accurately assess uncertainty of emission calculations. This update is necessary due to the extensive changes in emission calculation methodology, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N₂O emissions.

In the next Inventory report, updated AgSTAR anaerobic digester data will be incorporated. In addition, potential data sources (such as the USDA Agricultural Resource Management Survey) for updated WMS distribution estimates will be reviewed and discussed with USDA. Further, future Inventories may present emissions on a monthly basis to show seasonal emission changes for each WMS; this update would help compare these Inventory data to other data and models.

5.3 Rice Cultivation (IPCC Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013), and flooding creates anaerobic conditions that foster CH₄ production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH₄ produced by methanogenic bacteria is oxidized in the soil and converted to CO₂ by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH₄ into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH₄ 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 CH₄ emissions, 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 CH₄, but large amounts of CH₄ can be emitted in continuously irrigated fields, which is the most common practices 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 N₂O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have less living stems reaching the soil, thus reducing the amount of CH₄ transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH₄ 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 exudates⁵ 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 CH₄ emissions (Wassmann et al. 2000b). Fertilization practices also influences CH₄ emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linquist et al. 2012). Other environmental variables also impact the methanogenesis process such as soil

⁵ 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.

temperature and soil type. Soil temperature is an important factor regulating the activity of methanogenic bacteria which in turn affects the rate of CH₄ production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH₄ in the soil (Sass et al. 1994).

Rice is currently cultivated in twelve states, including Arkansas, California, Florida, Illinois, 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 sometimes grown in the Southeast. 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).

Overall, rice cultivation is a minor source of CH₄ emissions in the United States relative to other source categories (see Table 5-10 and Table 5-11). In 2014, CH₄ emissions from rice cultivation were 11.9 MMT CO₂ Eq. (476 kt). Annual emissions fluctuate between 1990 and 2014, and emissions in 2014 represented a 9 percent decrease compared to 1990. Variation in emissions is largely due to differences in the amount of rice harvested areas over time. In Arkansas and California, rice harvested areas increased by 33 percent and 39 percent respectively from 1990 to 2014, while rice harvested area declined in Louisiana and Texas by 14 percent and 78 percent respectively (see Table 5-12).

Table 5-10: CH₄ Emissions from Rice Cultivation (MMT CO₂ Eq.)

State	1990	2005	2010	2011	2012	2013	2014
Arkansas	2.8	4.2	4.5	4.5	4.6	4.6	4.6
California	1.7	2.5	2.4	2.4	2.4	2.4	2.4
Florida	+	+	+	+	+	+	+
Illinois	+	+	+	+	+	+	+
Louisiana	2.4	2.7	2.6	2.6	2.7	2.7	2.7
Minnesota	+	+	+	+	+	+	+
Mississippi	0.5	0.4	0.2	0.2	0.3	0.2	0.2
Missouri	0.3	0.5	0.7	0.7	0.7	0.7	0.7
New York	+	+	+	+	+	+	+
South Carolina	+	+	+	+	+	+	+
Tennessee	+	+	+	+	+	+	+
Texas	5.5	2.5	1.3	1.4	1.4	1.4	1.3
Total	13.1	13.0	11.9	11.8	11.9	11.9	11.9

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 5-11: CH₄ Emissions from Rice Cultivation (kt)

State	1990	2005	2010	2011	2012	2013	2014
Arkansas	113	169	182	182	182	182	182
California	70	101	94	94	94	94	94
Florida	+	2	+	+	+	+	+
Illinois	+	+	+	+	+	+	+
Louisiana	95	109	105	104	106	107	106
Minnesota	1	2	+	+	+	+	+
Mississippi	18	18	10	10	10	10	10
Missouri	10	20	29	29	29	29	29
New York	+	+	+	+	+	+	+
South Carolina	+	+	+	+	+	+	+
Tennessee	+	+	+	+	+	+	+
Texas	218	100	54	54	54	54	54
Total	525	521	474	474	476	477	476

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology

The methodology used to estimate CH₄ emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes a process-based model (DAYCENT) to estimate CH₄ 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 CH₄, as well as CH₄ transport through the plant and via ebullition (Cheng et al. 2013). The method simulates the influence of organic amendments and rice straw management on methanogenesis in the flooded soils. In addition to CH₄ emissions, DAYCENT simulates soil C stock changes and N₂O 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 CH₄ emissions from rice when grown in rotation with crops that are not simulated by DAYCENT, such as vegetables and perennial/horticultural crops. The Tier 1 method is 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 CH₄ emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaly 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 shaly mineral soils.

The Tier 1 method for estimating CH₄ emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission factor represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust 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).⁶

Rice cultivation areas are based on cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2013). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 survey points of which 2,072 are in locations with rice cultivation. The Tier 3 method is used to estimate CH₄ emissions from 1,852 of the NRI survey locations, and the remaining 220 survey locations are estimated with the Tier 1 method. Each NRI survey point is associated with an “expansion factor” that allows scaling of CH₄ 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 sample point). 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 2012 (USDA-NRCS 2015). This Inventory only uses NRI data through 2010 because newer data were not made available in time to incorporate the additional years of data. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2010	2011	2012	2013	2014
Arkansas	601	839	800	800	801	801	800
California	197	270	274	274	274	274	274
Florida	0	4	0	0	0	0	0
Illinois	0	1	0	0	0	0	0
Louisiana	365	375	315	313	317	316	315
Minnesota	5	6	1	1	1	1	1
Mississippi	104	113	53	53	53	53	53
Missouri	46	82	105	105	105	105	105
New York	0	0	0	0	0	0	0
South Carolina	0	0	0	0	0	0	0

⁶ See <<http://www.nrel.colostate.edu/projects/ALUsoftware/>>.

Tennessee	0	1	0	0	0	0	0
Texas	323	161	73	73	73	73	72
Total	1,641	1,852	1,621	1,619	1,624	1,622	1,620

Notes: Totals may not sum due to independent rounding. States are included if NRI reports rice areas at any time between 1990 and 2014.

The Southeastern states have sufficient growing periods for a ratoon crop in some years. For example, in Arkansas, the length of growing season is occasionally sufficient for ratoon crops on an average of 1 percent of the rice fields. 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 2014), averaging 32 percent and 48 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (45 percent). Ratoon rice crops are not grown in California. Ratooned crop area as a percent of primary crop area is presented in Table 5-13.

Table 5-13: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990–2014
Arkansas ^a	1%
California	0%
Florida ^b	45%
Louisiana ^c	32%
Mississippi ^a	1%
Missouri ^a	1%
Texas ^d	48%

^aArkansas: 1990–2000 (Slaton 1999 through 2001); 2001–2011 (Wilson 2002 through 2007, 2009 through 2012); 2012–2013 (Hardke 2013, 2014).

^bFlorida - 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)

^cLouisiana: 1990–2013 (Linscombe 1999, 2001 through 2014).

^dTexas: 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 the 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 CH₄ 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 the winter flood. 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 period.

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, and the uncertainties from each approach are combined to produce the final CH₄ emissions estimate using simple error

propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Rice cultivation CH₄ emissions in 2014 were estimated to be between 9.9 and 13.9 MMT CO₂ Eq. at a 95 percent confidence level, which indicates a range of 17 percent below to 17 percent above the actual 2014 emission estimate of 11.9 MMT CO₂ Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Rice Cultivation (MMT CO₂ Eq. and Percent)

Source	Inventory Method	2014 Emission Estimate		Uncertainty Range Relative to Emission Estimate ^a			
		Gas	(MMT CO ₂ Eq.)	(MMT CO ₂ Eq.)	Lower Bound	Upper Bound	Lower Bound
Rice Cultivation	Tier 3	CH ₄	10.7	8.8	12.6	-18%	18%
Rice Cultivation	Tier 1	CH ₄	1.2	0.8	1.6	-33%	40%
Rice Cultivation	Total	CH₄	11.9	9.9	13.9	-17%	17%

^aRange of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014 using the Tier 1 and 3 methods. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Some errors were found in the handling of the cropping rotations and management data for the DAYCENT simulations that were corrected. Data inputs to the ALU software for the Tier 1 method are checked to ensure proper handling of the data through the software. There was an error in the cultivation period that was corrected in the calculation of the emission factor. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in the reporting forms and text.

Model results are compared to field measurements to verify if results adequately represent CH₄ emissions. The comparisons included over 15 long-term experiments, representing about 800 combinations of management treatments across all of the sites. A statistical relationship was developed to assess uncertainties in the model structure and adjust for model bias and assess precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: (1) using the DAYCENT model to estimate CH₄ emissions from the majority of flooded rice production, (2) estimating CH₄ emissions from the remainder of the flooded rice area using a Tier 1 method, and (3) driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010. These changes resulted in an increase in emissions of approximately 30 percent on average relative to the previous Inventory and a decrease in uncertainty from confidence interval with a lower bound of 50 percent and upper bound of 91 percent to a confidence interval with an upper and lower bound of 17 percent.

Planned Improvements

Improvements are underway to update the land use and management data from the 2012 USDA NRI so that the time series of activity data are extended through 2012. Fertilization, tillage activity data, and water management will also be updated as part of this improvement to the extent that new data are available on these practices.

5.4 Agricultural Soil Management (IPCC 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).⁷ Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as symbiotic fixation of N from the atmosphere.⁸ A number of agricultural activities increase mineral N availability in soils that lead to direct N₂O emissions from nitrification and denitrification at the site of a management activity (see Figure 5-2) (Mosier et al. 1998), including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and drainage of organic soils (i.e., soils with a high organic matter content, otherwise known as Histosols⁹) in croplands and grasslands (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization by impacting moisture and temperature regimes in soils. Indirect emissions of N₂O occur when N is transported from a site and is subsequently converted to N₂O; 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.¹⁰

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; N₂O emissions from Forest Land and Settlements are found in Chapter 6). The U.S. Inventory includes all greenhouse gas emissions from managed land based on guidance in IPCC (2006), and consequently N mineralization from decomposition of soil organic matter and symbiotic N fixation are also included in this section to fully address emissions from the managed land base (see Methodology section for more information).

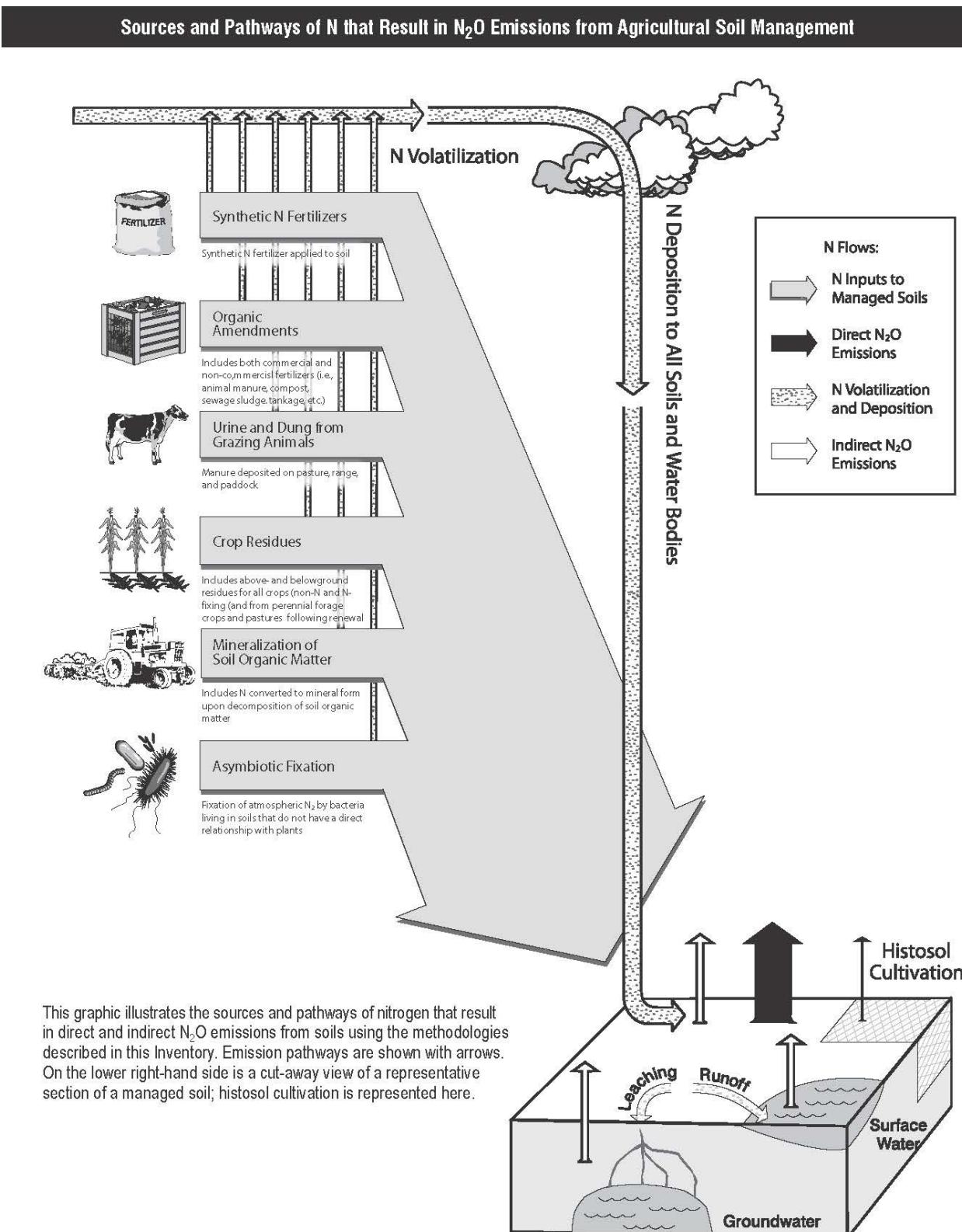
⁷ Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH₄⁺) to nitrate (NO₃⁻), and denitrification is the anaerobic microbial reduction of nitrate to N₂. Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

⁸ Asymbiotic N fixation is the fixation of atmospheric N₂ by bacteria living in soils that do not have a direct relationship with plants.

⁹ Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N₂O emissions from these soils.

¹⁰ These processes entail volatilization of applied or mineralized N as NH₃ and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH₄⁺, nitric acid (HNO₃), and NO_x.

Figure 5-2: Sources and Pathways of N that Result in N₂O Emissions from Agricultural Soil Management



Agricultural soils produce the majority of N₂O emissions in the United States. Estimated emissions from this source in 2014 are 318.4 MMT CO₂ Eq. (1,068 kt) (see Table 5-15 and Table 5-16). Annual N₂O emissions from agricultural soils fluctuated between 1990 and 2014, although overall emissions are 5 percent higher in 2014 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2014, on average cropland accounted for approximately 70 percent of total direct emissions, while grassland accounted for approximately 30 percent. The percentages for indirect emissions on average are approximately 65 percent for croplands, 35 percent for grasslands. Estimated direct and indirect N₂O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N₂O Emissions from Agricultural Soils (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Direct	245.0	248.3	263.8	264.5	264.5	261.2	261.0
Cropland	171.9	174.4	185.7	186.9	187.9	185.2	185.0
Grassland	73.2	73.9	78.1	77.6	76.6	76.0	76.0
Indirect	58.2	48.9	56.9	58.6	58.5	57.4	57.3
Cropland	36.2	34.0	39.7	40.6	41.1	40.3	40.2
Grassland	22.1	14.9	17.2	17.9	17.5	17.2	17.2
Total	303.3	297.2	320.7	323.1	323.1	318.6	318.4

Note: Totals may not sum due to independent rounding.

Table 5-16: N₂O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Direct	822	833	885	888	888	877	876
Cropland	577	585	623	627	630	621	621
Grassland	246	248	262	260	257	255	255
Indirect	195	164	191	196	196	193	192
Cropland	121	114	133	136	138	135	135
Grassland	74	50	58	60	59	58	58
Total	1,018	997	1,076	1,084	1,084	1,069	1,068

Note: Totals may not sum due to independent rounding.

Table 5-17: Direct N₂O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Cropland	171.9	174.4	185.7	186.9	187.9	185.2	185.0
Mineral Soils	168.6	171.2	182.6	183.9	184.9	182.2	182.0
Synthetic Fertilizer	59.2	61.4	59.3	61.0	61.8	59.5	59.3
Organic Amendment ^a	11.9	12.9	13.4	13.5	13.6	13.5	13.5
Residue N ^b	25.9	26.6	27.8	27.6	27.5	27.5	27.6
Mineralization and Asymbiotic Fixation	71.6	70.3	82.2	81.8	82.0	81.6	81.6
Drained Organic Soils	3.2	3.2	3.0	3.0	3.0	3.0	3.0
Grassland	73.2	73.9	78.1	77.6	76.6	76.0	76.0
Mineral Soils	70.3	71.0	75.5	74.9	74.0	73.3	73.3
Synthetic Fertilizer	1.1	1.3	1.3	1.2	1.2	1.2	1.4
PRP Manure	13.4	12.3	12.5	11.9	11.0	10.3	10.3
Managed Manure ^c	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Sewage Sludge	0.2	0.5	0.5	0.5	0.6	0.6	0.6
Residue N ^d	19.7	21.0	21.8	21.7	21.7	21.7	21.6
Mineralization and Asymbiotic Fixation	35.8	35.8	39.1	39.4	39.4	39.4	39.2
Drained Organic Soils	2.9	2.9	2.7	2.7	2.7	2.7	2.7
Total	245.0	248.3	263.8	264.5	264.5	261.2	261.0

^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 5-18: Indirect N₂O Emissions from Agricultural Soils (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
Cropland	36.2	34.0	39.7	40.6	41.1	40.3	40.2
Volatilization & Atm.							
Deposition	13.0	13.8	13.9	14.3	14.5	14.2	14.2
Surface Leaching & Run-Off	23.2	20.2	25.8	26.4	26.6	26.0	26.0
Grassland	22.1	14.9	17.2	17.9	17.5	17.2	17.2
Volatilization & Atm.							
Deposition	4.4	4.7	4.8	4.7	4.6	4.5	4.5
Surface Leaching & Run-Off	17.7	10.2	12.4	13.2	12.9	12.6	12.6
Total	58.2	48.9	56.9	58.6	58.5	57.4	57.3

Note: Totals may not sum due to independent rounding.

Figure 5-3 and Figure 5-4 show regional patterns for direct N₂O emissions for croplands and grasslands, and Figure 5-5 and Figure 5-6 show N losses from volatilization, leaching, and runoff that lead to indirect N₂O emissions. Annual emissions and N losses in 2014 are shown for the Tier 3 Approach only.

Direct N₂O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern and western Minnesota, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (see Figure 5-3). Kansas has high direct emissions associated with N management in wheat production systems, in addition to high emissions in North and South Dakota. Hay production in Missouri also contribute relatively large amounts of direct N₂O emissions, along with a combination of irrigated cropping in west Texas and hay production in east Texas. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated as well as in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are highest in the central and western United States (see Figure 5-4) where a high proportion of the land is used for cattle grazing. In contrast, most areas in the Great Lake states, the Northeast, and Southeast have moderate to low emissions due to less land dedicated to livestock grazing. However, emissions from the Northeast and Great Lake states tend to be higher on a per unit area basis compared to other areas in the country. This effect is likely due to a larger impact of freeze-thaw cycles in these regions, and possibly greater water-filled pore space in the soil, which are key drivers of N₂O emissions (Kessavalou et al. 1998; Bateman and Baggs 2005).

Nitrogen losses from croplands and grasslands that lead to indirect N₂O emissions (Figure 5-5 and Figure 5-6) have similar spatial patterns as direct N₂O emissions. This is not surprising because N losses leading to indirect N₂O emissions are influenced by the same variables that drive direct N₂O emissions (N inputs, weather patterns, and soil characteristics). However, there are some exceptions to the similarity in patterns. For example, there are limited amounts of nitrate leaching from western grasslands due to lower precipitation and leaching through the soil profile, compared to grasslands in the central United States, whereas the N₂O emissions are higher in the western grasslands.

Figure 5-3: Crops, 2014 Annual Direct N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

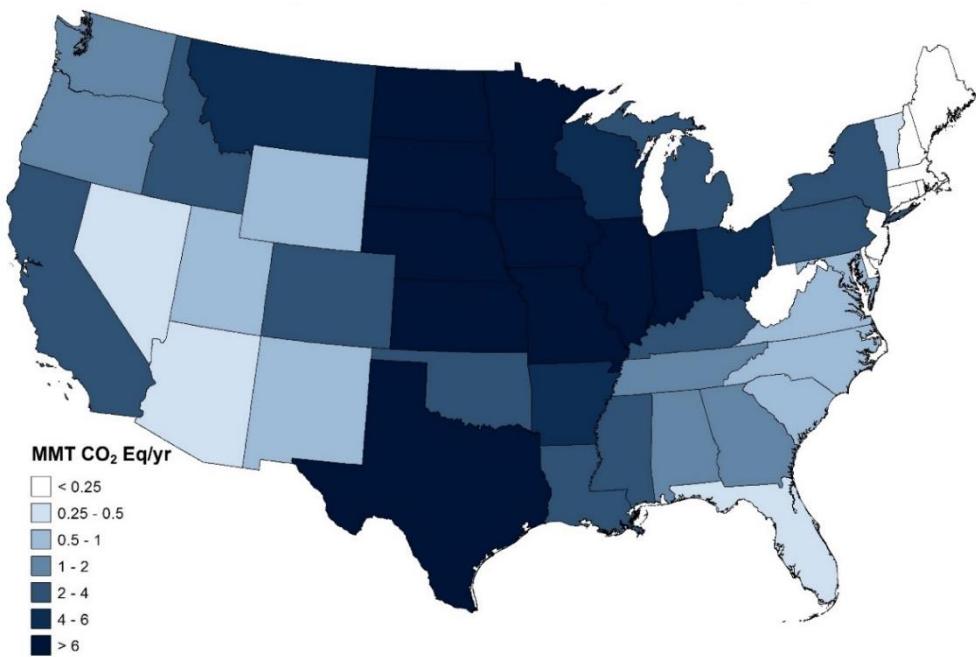


Figure 5-4: Grasslands, 2014 Annual Direct N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (MMT CO₂ Eq./year)

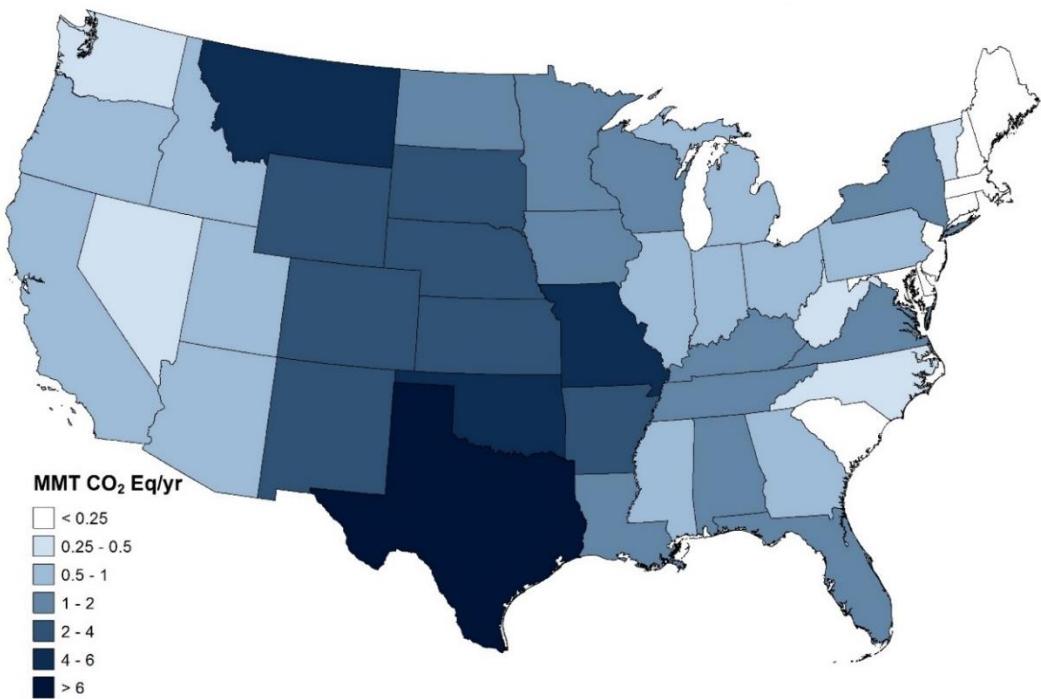


Figure 5-5: Crops, 2014 Average Annual N Losses Leading to Indirect N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (kt N/year)

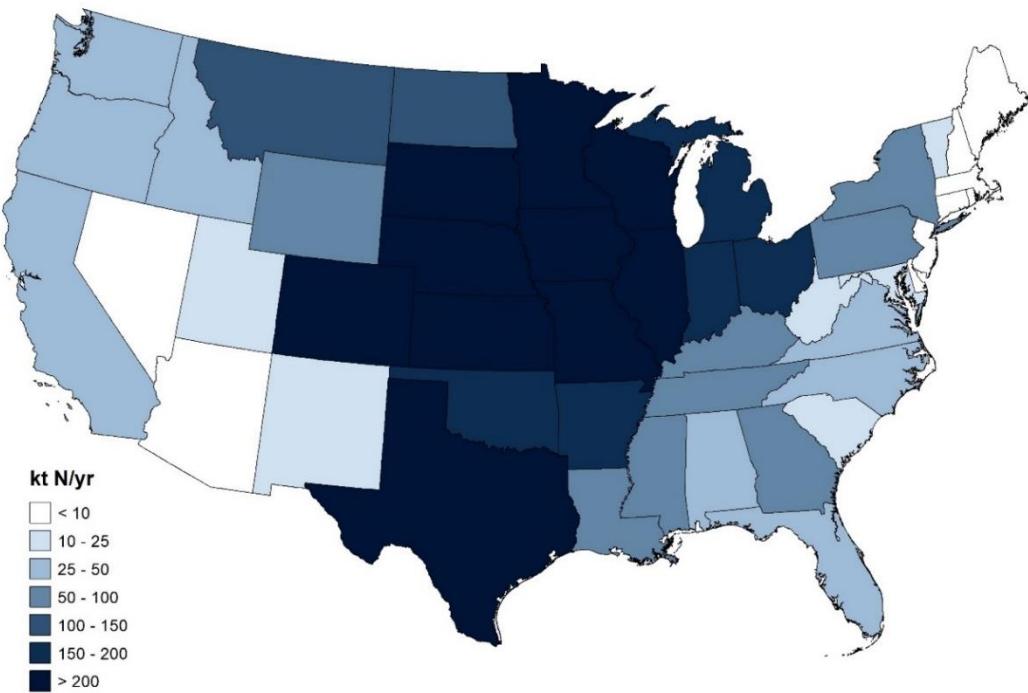
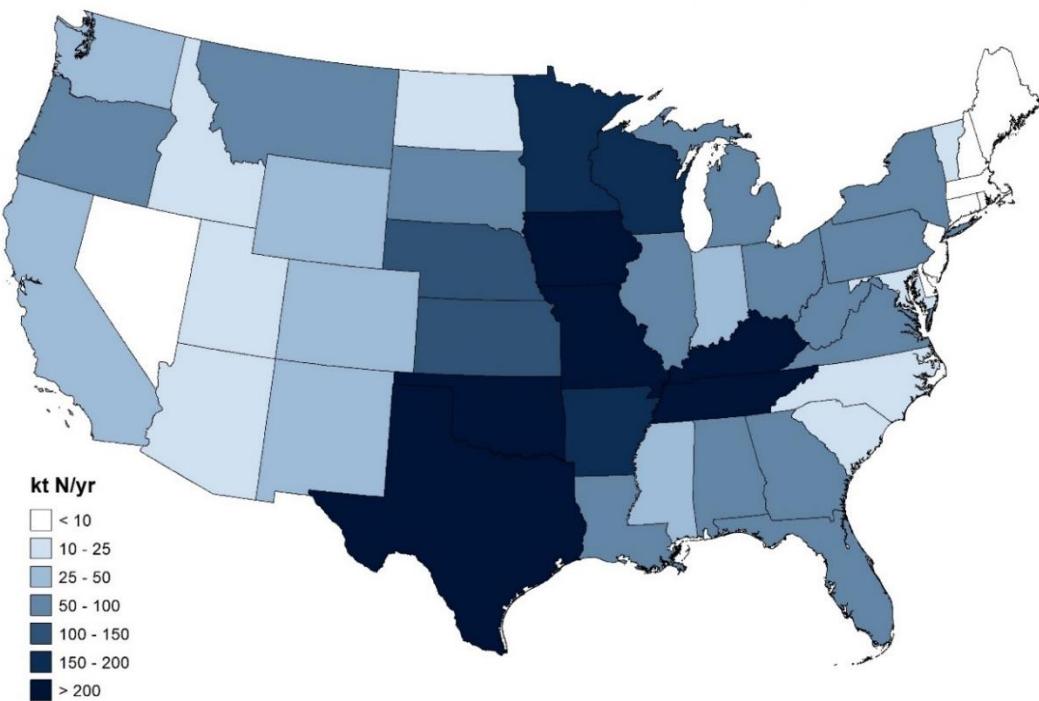


Figure 5-6: Grasslands, 2014 Average Annual N Losses Leading to Indirect N₂O Emissions Estimated Using the Tier 3 DAYCENT Model (kt N/year)



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, sewage sludge applications, crop residues, organic amendments, and biological N fixation associated with planting of legumes on cropland and grassland soils; (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 N₂O.

The United States has adopted methods in the IPCC (2006) for the Agricultural Soil Management source category. These methods include (1) estimating the contribution of N in crop residues to indirect soil N₂O emissions; (2) adopting the revised emission factor for direct N₂O emissions for Tier 1 methods used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils from harvest yield data; and (5) estimating emissions associated with land use and management change (which can significantly change the N mineralization rates from soil organic matter). The Inventory also reports on total emissions from all managed land, which is a proxy for anthropogenic impacts on greenhouse gas emissions (IPCC 2006), including direct and indirect N₂O emissions from asymbiotic fixation¹¹ and mineralization of soil organic matter and litter. 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 N₂O Emissions

The methodology used to estimate direct N₂O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches (IPCC 2006; Del Grosso et al. 2010). 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, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat; as well as the direct emissions from non-federal grasslands with the exception of sewage sludge amendments (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N₂O emissions in the United States, accounting for more of the environmental and management influences on soil N₂O emissions than the IPCC Tier 1 method (see Box 5-1 for further elaboration). Moreover, the Tier 3 approach allows for the Inventory to address direct N₂O 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 N₂O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are taken into account between C and N cycling in soils.

The Tier 3 approach is based on the cropping and land use histories recorded in the USDA NRI survey (USDA-NRCS 2013). The NRI is a statistically-based sample of all non-federal land, and includes 380,956 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 the remaining 92,013 in the NRI survey that are designated as cropland or grassland (discussed later in this section). Each point is associated with an “expansion factor” that allows scaling of N₂O 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 sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. 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, the annual

¹¹ N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this source.

data are currently available through 2012 (USDA-NRCS 2015) although this Inventory only uses NRI data through 2010 because newer data were not made available in time to incorporate the additional years into this Inventory.

Box 5-1: Tier 1 vs. Tier 3 Approach for Estimating N₂O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N₂O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) that represents the interaction of N inputs, land use and management, as well as environmental conditions at specific locations. Consequently, the Tier 3 approach produces more accurate estimates; it accounts more comprehensively for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N amendment rates), additional data inputs (i.e., daily weather, soil types, etc.), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N₂O emissions only during that year and cannot be stored in soils and contribute to N₂O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N₂O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N₂O during subsequent years.

DAYCENT is used to estimate N₂O emissions associated with production of alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat, but is not applied to estimate N₂O emissions from other crops or rotations with other crops,¹² such as sugarcane, some vegetables, tobacco, 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 (greater than 35 percent by volume), 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 on land use histories. For areas that are not included in the DAYCENT simulations, the Tier 1 IPCC (2006) methodology is used to estimate (1) direct emissions from crops on mineral soils that are not simulated by DAYCENT; (2) direct emissions from Pasture/Range/Paddock (PRP) on federal grasslands; and (3) direct emissions from drained organic soils in croplands and grasslands.

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 N₂O emissions from mineral cropland soils that are managed for production of a wide variety of crops based on the cropping histories in the 2010 NRI (USDA-NRCS 2013). The crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Crops simulated by DAYCENT are grown on approximately 91 percent of total cropland area in the United States. For agricultural systems in the central region of the United States, crop production for key crops (i.e., corn, soybeans, sorghum, cotton, and wheat) is simulated in DAYCENT with a

¹² 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.

NASA-CASA production algorithm (Potter et al. 1993; Potter et al. 2007) using the Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, with a pixel resolution of 250m.¹³

DAYCENT is used to estimate direct N₂O emissions due to mineral N available from the following sources: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues 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 soil organic matter; and (5) symbiotic fixation. Note that commercial organic fertilizers (TVA 1991 through 1994; AAPFCO 1995 through 2014) are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model.

Synthetic fertilizer data are based on fertilizer use and rates by crop type for different regions of the United States that are obtained primarily from the USDA Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of livestock manure application to cropland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. The adjustments are based on county-scale ratios of manure available for application to soils in other years relative to 1997 (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application is estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and including the addition of N from bedding materials. Nitrogen losses include direct N₂O emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. For unmanaged systems, it is assumed that no N losses or additions occur prior to the application of manure to the soil. More information on livestock manure production is available in the Manure Management Section 5.2 and Annex 3.11.

The IPCC approach 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 symbiotic 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 symbiotic N fixation on N₂O emissions, but these are not model inputs. The N₂O emissions from crop residues are reduced by approximately 3 percent to avoid double-counting associated with non-CO₂ greenhouse gas emissions from agricultural residue burning. The estimate of residue burning is based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Additional sources of data are used to supplement the mineral N (USDA ERS 1997, 2011), livestock manure (Edmonds et al. 2003), and land-use information (USDA-NRCS 2013). The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity with adjustments for long-term adoption of no-till agriculture (Towery 2001). Tillage data has an influence on soil organic matter decomposition and subsequent soil N₂O emissions. The time series of tillage data began in 1989 and ended in 2004, so further changes in tillage practices since 2004 are not currently captured in the Inventory. Daily weather data are used as an input in the model simulations, based on gridded weather data at a 32 km scale from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011).

Each 2010 NRI point is run 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulations for the analysis. Soil N₂O 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). Soil N₂O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but emissions from 2011 to 2014 are assumed to be similar to 2010. Annual data are currently available through 2012

¹³ See <https://lpdaac.usgs.gov/products/modis_products_table>.

(USDA-NRCS 2015), however this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years.

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 N₂O production (nitrification and denitrification). It is not possible to partition N₂O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N₂O 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 is determined for each source of mineral N 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 N₂O emissions in order to approximate the portion attributed to key 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 N₂O, 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 N₂O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N₂O emissions for mineral cropland soils that are not simulated by DAYCENT. For the Tier 1 Approach, estimates of direct N₂O 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 not included in the DAYCENT simulations because county-level data are not available.¹⁴ Consequently, commercial organic fertilizer, as well as additional 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 not simulated by DAYCENT. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS from sales records (Ruddy et al. 2006), and these data are aggregated to obtain state-level N additions to farms. For 2002 through 2014, state-level fertilizer for on-farm use is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2007; AAPFCO 2008 through 2014).¹⁵ After subtracting the portion of fertilizer applied to crops and grasslands simulated by DAYCENT (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section 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 amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total manure N available for land application (see Tier 3 Approach for Cropland Mineral Soils Section and Grasslands Section for information on data sources), and 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 to units of N using average organic fertilizer N content (TVA 1991 through 1994, AAPFCO 1995 through 2011). Commercial fertilizers do include some manure and sewage sludge, but the amounts

¹⁴ Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and sewage sludge is removed from the dataset in order to avoid double counting with other datasets that are used for manure N and sewage sludge.

¹⁵ Values are not available for 2013 and 2014 so a “least squares line” statistical extrapolation using the previous 5 years of data is used to arrive at an approximate value for these two years.

are removed from the commercial fertilizer data to avoid double counting with the manure N dataset described above and the 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 2013), crop production yield statistics (USDA-NASS 2014), 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).

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 N₂O emissions using the Tier 1 Approach.

Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 methods are used to estimate direct N₂O emissions due to drainage of organic soils in croplands or grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2010 NRI (USDA-NRCS 2013) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). Temperature data from Daly et al. (1994 and 1998) are used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006). Annual data are available between 1990 and 2010. Emissions are assumed to be similar to 2010 from 2011 to 2014 because no additional activity data are currently available from the NRI for the latter years. 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).

Direct N₂O Emissions from Grassland Soils

As with N₂O 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 forage primarily 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 legumes. DAYCENT is used to simulate N₂O emissions from NRI survey locations (USDA-NRCS 2013) 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), 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 symbiotic 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 for Mineral Cropland Soils section. Managed manure N amendments to grasslands are estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils, according to methods described in the Manure Management section (Section 5.2) and Annex 3.11. 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) is another key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI point are based on amount of N excreted by livestock in PRP systems. 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 input rates are used in the DAYCENT simulations. DAYCENT simulations of non-federal grasslands accounted for approximately 72 percent of total PRP manure N in aggregate across the country. The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N₂O emissions are estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Sewage sludge is assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments to agricultural lands are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at the county scale. Therefore, DAYCENT could not be used to simulate the influence of sewage sludge amendments on N₂O emissions from grassland soils, and consequently, emissions from sewage sludge are estimated using the IPCC (2006) Tier 1 method.

Grassland area data are obtained from the U.S. Department of Agriculture NRI (Nusser and Goebel 1998) and the U.S. Geological Survey (USGS) National Land Cover Dataset (Vogelman et al. 2001), which are reconciled with the Forest Inventory and Analysis Data. The area data for pastures and rangeland are aggregated to the county level to estimate non-federal and federal grassland areas.

N_2O emissions for the PRP manure N deposited on federal grasslands and applied sewage sludge N are estimated using the Tier 1 method by multiplying the N input by the appropriate emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from sewage sludge N are calculated exclusively at the national scale.

As previously mentioned, each NRI point is simulated 100 times as part of the uncertainty assessment, yielding a total of over 18 million simulation runs for the analysis. 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). Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but emissions from 2011 to 2014 are assumed to be similar to 2010. The annual data are currently available through 2012 (USDA-NRCS 2015), however this Inventory only uses NRI data through 2010 because newer data were not made available in time to incorporate the additional years into this Inventory.

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 5-15 and Table 5-16).

Indirect N_2O Emissions

This section describes the methods used for estimating indirect soil N_2O emissions from croplands and grasslands. Indirect N_2O emissions occur when mineral N 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, sewage sludge), 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.

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 Cropland Mineral Soils section and Grasslands section. Nitrogen volatilization for all other areas is estimated using the Tier 1 method and 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, sewage sludge application on grasslands). For the volatilization data generated from both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions occurring due to re-deposition of the volatilized N (see Table 5-18).

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 N₂O. 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. This N transport estimate includes N applications on croplands that are not simulated by DAYCENT, sewage sludge amendments 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 N₂O 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 plus irrigation does not exceed 80 percent of PET. 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 N₂O emissions that occur in groundwater and waterways (see Table 5-18).

Uncertainty and Time-Series Consistency

Uncertainty is estimated for each of the following five components of N₂O 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 approximated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) approximated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which account for the majority of N₂O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT are estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). Uncertainties in direct emissions calculated with the IPCC (2006) Approach 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Approach 1 method, and indirect N₂O emissions are estimated with a simple error propagation approach (IPCC 2006). Uncertainties from the Approach 1 and Approach 3 (i.e., DAYCENT) estimates are combined using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Table 5-19 shows the combined uncertainty for direct soil N₂O emissions ranged from 16 percent below to 24 percent above the 2014 emissions estimate of 261.0 MMT CO₂ Eq., and the combined uncertainty for indirect soil N₂O emissions range from 47 percent below to 139 percent above the 2014 estimate of 57.3 MMT CO₂ Eq.

Table 5-19: Quantitative Uncertainty Estimates of N₂O Emissions from Agricultural Soil Management in 2014 (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)		Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.) (%)			
		Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N ₂ O Emissions	N ₂ O	261.0	219.4	323.8	-16%	24%	
Indirect Soil N ₂ O Emissions	N ₂ O	57.3	30.6	137.0	-47%	139%	

Notes: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

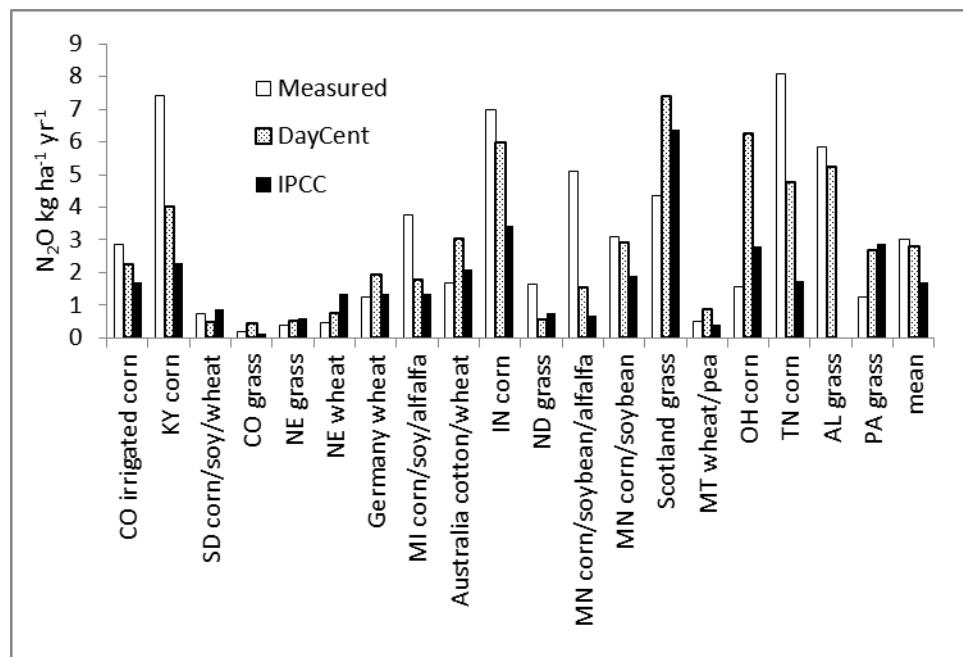
Additional uncertainty is associated with an incomplete estimation of all N₂O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory only includes the N₂O emissions from mineral fertilizer additions in Alaska and Hawaii, and drained organic soils in Hawaii. Agriculture is not extensive in either state, so the emissions are likely to be small for the other sources of N (e.g., manure amendments), which are not currently included in the Inventory, compared to the conterminous United States.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends are described in more detail in the Methodology section above.

QA/QC and Verification

DAYCENT results for N₂O emissions and NO₃⁻ 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 are available for 27 sites, which mostly occur in the United States, with four in Europe and one in Australia, representing over 75 different combinations of fertilizer treatments and cultivation practices. Nitrate leaching data are available for four sites in the United States, representing 12 different combinations of fertilizer amendments/tillage practices. DAYCENT estimates of N₂O emissions are closer to measured values at most sites compared to the IPCC Tier 1 estimate (see Figure 5-7). In general, the IPCC Tier 1 methodology tends to over-estimate emissions when observed values are low and under-estimate emissions when observed values are high, while DAYCENT estimates have less bias. DAYCENT accounts for key site-level factors (i.e., weather, soil characteristics, and management) that are not addressed in the IPCC Tier 1 Method, and thus the model is better able to represent the variability in N₂O emissions. DAYCENT does have a tendency to under-estimate very high N₂O emission rates; and estimates are adjusted using the statistical model derived from the comparison of model estimates to measurements (see Annex 3.12 for more information). Regardless, the comparison demonstrates that DAYCENT provides relatively high predictive capability for N₂O emissions, and is an improvement over the IPCC Tier 1 method.

Figure 5-7: Comparison of Measured Emissions at Field Sites and Modeled Emissions Using the DAYCENT Simulation Model and IPCC Tier 1 Approach (kg N₂O per ha per year)



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 been checked, updated, and corrected when necessary. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach have been checked and updated as needed.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: (1) driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010; (2) accounting for N inputs from residues associated with additional crops not simulated by DAYCENT including most vegetable crops; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N₂O emissions; and (4) using DAYCENT for direct N₂O emissions from most flooded rice lands, instead of using the Tier 1 approach for all rice lands. These changes resulted in an increase in emissions of approximately 24 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N₂O emissions from 26 to 24 percent. The differences in emissions and uncertainty are mainly due to increasing the number of study sites used to quantify model uncertainty.

Planned Improvements

Several planned improvements are underway.

- Land use and management data will be updated with the 2012 USDA NRI so that the time series of activity data are extended through 2012. Fertilization and tillage activity data will also be updated as part of this improvement. In addition, the remote-sensing based data on the EVI will be extended through 2012 in order to use the EVI data to drive crop production in DAYCENT.
- The DAYCENT biogeochemical model will be improved with a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature 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 N₂O emissions. An improved representation of drainage is also under development. Experimental study sites will continue to be added for quantifying model structural uncertainty, and studies that have continuous (daily) measurements of N₂O (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 5.5). See the Planned Improvement section in the Field Burning of Agricultural Residues section for more information.
- Alaska and Hawaii are not included in the current Inventory for agricultural soil management, with the exception of N₂O emissions from drained organic soils in croplands and grasslands for Hawaii. A planned improvement over the next two years is to add these states into the Inventory analysis.
- Use the new Tier 1 emission factor for N₂O emissions from drained organic soils that is provided in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2013).

5.5 Field Burning of Agricultural Residues (IPCC 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 CO₂ emissions because the C released to the atmosphere as CO₂ during burning is reabsorbed during the next growing season for the crop. However, crop residue burning is a net source of CH₄, N₂O, 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). Rice, sugarcane, and wheat residues account for approximately 70 percent of all crop residue burning and emissions (McCarty 2011). In 2014, CH₄ and N₂O emissions from field burning of agricultural residues were 0.3 MMT CO₂ Eq. (11 kt) and 0.1 MMT CO₂ Eq. (0.3 kt), respectively. Furthermore, annual emissions from this source from 1990 to 2014 have remained relatively constant, averaging approximately 0.3 MMT CO₂ Eq. (10 kt) of CH₄ and 0.1 MMT CO₂ Eq. (0.3 kt) of N₂O (see Table 5-20 and Table 5-21).

Table 5-20: CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq.)

Gas/Crop Type	1990	2005	2010	2011	2012	2013	2014
CH₄	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Wheat	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
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
N₂O	0.1						
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
Total	0.3	0.3	0.4	0.4	0.4	0.4	0.4

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: Totals may not sum due to independent rounding.

Table 5-21: CH₄, N₂O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2010	2011	2012	2013	2014
CH₄	10	8	11	11	11	11	11
Wheat	5	4	5	5	5	5	5
Rice	2	2	2	2	2	2	2
Sugarcane	1	1	1	1	1	1	2
Corn	1	1	1	1	1	1	2
Soybeans	1	1	1	1	1	1	1
Lentil	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
N₂O	+						
Wheat	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Lentil	+	+	+	+	+	+	+
CO	202	177	229	233	234	238	238
NO_x	6	6	7	8	8	8	8

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding

Methodology

A U.S.-specific Tier 2 method was used to estimate greenhouse gas emissions from field burning of agricultural residues (for more details, see Box 5-2). In order to estimate the amounts of C and N released during burning, the following equation was used:

$$C \text{ or } N \text{ released} = \Sigma \text{ for all crop types and states} \left[\frac{AB}{CAH \times CP \times RCR \times DMF \times BE \times CE \times (FC \text{ or } FN)} \right]$$

where,

Area Burned (AB)	= Total area of crop burned, by state
Crop Area Harvested (CAH)	= Total area of crop harvested, by state
Crop Production (CP)	= Annual production of crop in kt, by state
Residue: Crop Ratio (RCR)	= Amount of residue produced per unit of crop production
Dry Matter Fraction (DMF)	= Amount of dry matter per unit of biomass for a crop
Fraction of C or N (FC or FN)	= Amount of C or N per unit of dry matter for a crop
Burning Efficiency (BE)	= The proportion of prefire fuel biomass consumed ¹⁶
Combustion Efficiency (CE)	= The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively

Crop Production and Crop Area Harvested were available by state and year from USDA (2014) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH₄, CO, N₂O, and NO_x emissions from the field burning of agricultural residues:

$$\begin{aligned} & \text{CH}_4 \text{ and CO, or N}_2\text{O and NO}_x \text{ Emissions from Field Burning of Agricultural Residues} = \\ & \quad C \text{ or } N \text{ Released} \times ER \times CF \end{aligned}$$

where,

Emissions Ratio (ER)	= g CH ₄ -C or CO-C/g C released, or g N ₂ O-N or NO _x -N/g N released
Conversion Factor (CF)	= conversion, by molecular weight ratio, of CH ₄ -C to C (16/12), or CO-C to C (28/12), or N ₂ O-N to N (44/28), or NO _x -N to N (30/14)

Box 5-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from field burning of agricultural residues were calculated using a Tier 2 methodology that is based on method developed by the IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. 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; and (3) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from seven crops (corn, cotton, lentils, rice, soybeans, sugarcane, and wheat).

A comparison of the methods and factors used in: (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken in the 1990 through 2014 Inventory report to determine the difference in overall estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residue using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used:

$$\text{Emissions (kt)} = AB \times (M_B \times C_f) \times G_{ef} \times 10^{-6}$$

¹⁶ In IPCC/UNEP/OECD/IEA (1997), the equation for C or N released contains the variable ‘fraction oxidized in burning’. This variable is equivalent to (burning efficiency × combustion efficiency).

where,

Area Burned (AB)	= Total area of crop burned (ha)
Mass Burned ($M_B \times C_f$)	= IPCC (2006) default fuel biomass consumption (metric tons dry matter burnt ha^{-1})
Emission Factor (G_{ef})	= IPCC (2006) emission factor ($g kg^{-1}$ dry matter burnt)

The IPCC (2006) default approach resulted in 5 percent higher emissions of CH₄ and 21 percent higher emissions of N₂O compared to this Inventory (and are within the uncertainty ranges estimated for this source category). The IPCC/UNEP/OECD/IEA (1997) is considered a more appropriate method for U.S. conditions because it is more flexible for incorporating country-specific data compared to IPCC (2006) approach for Tier 1 and 2 methods.

Crop yield data (except rice in Florida) were based on USDA's QuickStats (USDA 2015), and crop area data were based on the 2010 NRI (USDA 2013). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields was multiplied by the NRI crop areas. Rice yield data for Florida was estimated separately because yield data were not collected by USDA. Total rice production for Florida was determined using NRI crop areas and total yields were based on average primary and ratoon rice yields from Schueneman and Deren (2002). Relative proportions of ratoon crops were derived from information in several publications (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007 through 2014). The production data for the crop types whose residues are burned are presented in Table 5-22. Crop weight by bushel was obtained from Murphy (1993).

The fraction of crop area burned was calculated using data on area burned by crop type and state¹⁷ from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat.¹⁸ McCarty (2010) used remote sensing data from MODIS to estimate area burned by crop. State-level area burned data were divided by state-level crop area harvested data to estimate the percent of crop area burned by crop type for each state. The average percentage of crop area burned at the national scale is shown in Table 5-23. Data on fraction of crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average over the five-year period from 2003 to 2007. Table 5-23 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

All residue: crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue: crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997), and the N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents of cotton are from Lachnicht et al. (2004). The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types, except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). See Table 5-24 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases were based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-25).

¹⁷ Alaska and Hawaii were excluded.

¹⁸ McCarty (2009) also examined emissions from burning of Kentucky bluegrass and a general "other crops/fallow" category, but USDA crop area and production data were insufficient to estimate emissions from these crops using the methodology employed in the Inventory. McCarty (2009) estimates that approximately 18 percent of crop residue emissions result from burning of the Kentucky bluegrass and "other crops" categories.

Table 5-22: Agricultural Crop Production (kt of Product)

Crop	1990	2005	2010	2011	2012	2013	2014
Corn ^a	229,257	300,965	335,669	321,920	270,310	350,472	378,574
Cotton	4,446	6,811	4,814	4,369	5,156	4,841	5,104
Lentils	38	248	406	234	251	271	156
Rice	8,907	12,596	11,376	11,795	12,547	12,932	12,874
Soybeans	55,178	86,908	94,467	90,761	86,922	95,473	103,588
Sugarcane	31,827	32,496	30,333	32,469	34,925	34,186	34,160
Wheat	79,011	70,074	71,017	62,131	71,094	68,772	64,748

^a Corn for grain (i.e., excludes corn for silage).

Table 5-23: U.S. Average Percent Crop Area Burned by Crop (Percent)

State	1990	2005	2010	2011	2012	2013	2014
Corn	+	+	+	+	+	+	+
Cotton	1%	1%	1%	1%	1%	1%	1%
Lentils	2%	+	+	1%	1%	1%	1%
Rice	9%	5%	7%	7%	7%	7%	7%
Soybeans	+	+	+	+	+	+	+
Sugarcane	10%	14%	23%	25%	23%	22%	24%
Wheat	2%	2%	2%	3%	2%	2%	2%

+ Does not exceed 0.5 percent.

Table 5-24: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue: Crop Ratio	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	1.0	0.91	0.448	0.006	0.93	0.88
Cotton	1.6	0.90	0.445	0.012	0.93	0.88
Lentils	2.0	0.85	0.450	0.023	0.93	0.88
Rice	1.4	0.91	0.381	0.007	0.93	0.88
Soybeans	2.1	0.87	0.450	0.023	0.93	0.88
Sugarcane	0.2	0.62	0.424	0.004	0.81	0.68
Wheat	1.3	0.93	0.443	0.006	0.93	0.88

Table 5-25: 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 ₂ O: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).

Uncertainty and Time-Series Consistency

The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 5-26. Methane emissions from field burning of agricultural residues in 2014 were estimated to be between 0.16 and 0.38 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 40 percent below and 40 percent above the 2014 emission estimate of 0.3 MMT CO₂ Eq. Also at the 95 percent confidence level, N₂O emissions were estimated to be between

0.07 and 0.12 MMT CO₂ Eq., or approximately 29 percent below and 29 percent above the 2014 emission estimate of 0.1 MMT CO₂ Eq.

Table 5-26: Approach 2 Quantitative Uncertainty Estimates for CH₄ and N₂O Emissions from Field Burning of Agricultural Residues (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.) (%)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH ₄	0.3	0.16	0.38	-40%	40%
Field Burning of Agricultural Residues	N ₂ O	0.1	0.07	0.12	-29%	29%

^aRange 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 omission of burning associated with Kentucky bluegrass and “other crop” residues. Methodological recalculations were applied to the entire time series, ensuring time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section above.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented with Tier 1 and 2 analyses. The Tier 1 analysis conducted this year uncovered a data transcription error in the corn production data for 1990. No other errors were found.

Recalculations Discussion

The source data for crop areas was changed from USDA NASS QuickStats to the 2010 NRI. This change ensures greater consistency in the land representation across cropland source categories, including direct and indirect soil nitrous oxide emissions in Agricultural Soil Management, and soil carbon stock changes in the *Cropland Remaining Cropland* and *Land Converted to Cropland* sections, which also rely on the NRI data as the basis for crop areas. The NRI data were used to recalculate percent crop area burned and total crop production. This change resulted in higher crop production estimates (ranging from 4 to 40 percent) and lower burned area percentages (ranging from -2 to -42 percent), compared to the previous Inventory. However, the overall impact on the recalculated emissions was relatively small, with CH₄ and N₂O emissions decreasing by 12 and 7 percent respectively. Correcting a transcription error in crop production for corn in 1990 (see Table 5-22) led to a larger recalculations in emissions for 1990 relative to the other years.

Planned Improvements

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 the DAYCENT model, and burning events will be simulated directly within the process-based model framework using information derived from remote sensing fire products. This improvement will lead to greater consistency in the methods for these sources, and better ensure mass balance of C and N in the Inventory analysis.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux resulting from the use and conversion of land-use categories in the United States.¹ The Intergovernmental Panel on Climate Change 2006 *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between certain land-use types termed: Forest Land, Cropland, Grassland, Settlements, Wetlands (as well as Other Land). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest ecosystem carbon (C) stocks, harvested wood pools, non-carbon dioxide (non-CO₂) emissions from forest fires, and the application of synthetic fertilizers to forest soils. Only fluxes for C stock changes from mineral soils are included for *Land Converted to Forest Land*. 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 organic C stocks in mineral and organic soils due to land use and management, emissions of CO₂ due to the application of crushed limestone and dolomite to managed land (i.e., soil liming), urea fertilization and the change in aboveground biomass C stocks for *Forest Land Converted to Cropland* and *Forest Land Converted to Grassland*.² Fluxes from *Wetlands Remaining Wetlands* include CO₂, methane (CH₄) and nitrous oxide (N₂O) emissions from managed peatlands; estimates for *Land Converted to Wetlands* are currently not available. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and application of nitrogen fertilizer to soils; fluxes from *Land Converted to Settlements* are currently not available. Landfilled yard trimmings and food scraps are accounted for separately under *Other*.

Land use, land-use change, and forestry (LULUCF) activities in 2014 resulted in a net increase in C stocks (i.e., net CO₂ removals) of 787.0 MMT CO₂ Eq. (214.6 MMT C).³ This represents an offset of approximately 11.5 percent of total (i.e., gross) greenhouse gas emissions in 2014. Emissions from land use, land-use change, and forestry activities in 2014 are 24.6 MMT CO₂ Eq. and represent 0.4 percent of total greenhouse gas emissions.⁴

Total C sequestration in the LULUCF sector increased by approximately 4.5 percent between 1990 and 2014. This increase was primarily due to an increase in the rate of net C accumulation in forest and urban tree C stocks.⁵ Net C accumulation in *Forest Land Remaining Forest Land* and *Settlements Remaining Settlements* increased, while net C

¹ The term “flux” is used to describe the net emissions of greenhouse gases accounting for both the emissions of CO₂ to and the removals of CO₂ from the atmosphere. Removal of CO₂ from the atmosphere is also referred to as “carbon sequestration”.

² Direct and indirect emissions of N₂O from inputs of N to cropland and grassland soils are included in the Agriculture Chapter.

³ Net CO₂ flux 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*, *Settlements Remaining Settlements*, and *Other*.

⁴ LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

⁵ 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.

accumulation in *Land Converted to Forest Land*, *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, and *Landfilled Yard Trimmings and Food Scraps* slowed over this period. Emissions from *Land Converted to Cropland* and *Wetlands Remaining Wetlands* decreased, while emissions from *Land Converted to Grassland* increased. Net C stock change from LULUCF is summarized in Table 6-1.

Table 6-1: Net C Stock Change from Land Use, Land-Use Change, and Forestry (MMT CO₂ Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Forest Land Remaining Forest Land	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Changes in Forest Carbon Stock ^a	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Land Converted to Forest Land	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Changes in Forest Carbon Stock	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Cropland Remaining Cropland	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
Changes in Agricultural Carbon Stock ^b	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
Land Converted to Cropland	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Changes in Agricultural Carbon Stock ^b	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Grassland Remaining Grassland	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Changes in Agricultural Carbon Stock ^b	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Land Converted to Grassland	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Changes in Agricultural Carbon Stock ^b	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Settlements Remaining Settlements	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Changes in Carbon Stocks in Urban							
Trees	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Other	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
Landfilled Yard Trimmings and Food							
Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
LULUCF Total Net Flux	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)

^a Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^b Estimates include C stock changes in all pools.

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

Emissions from LULUCF activities are shown in Table 6-2. Liming and urea fertilization in 2014 resulted in CO₂ emissions of 8.7 MMT CO₂ Eq. (8,653 kt of CO₂). Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO₂ emissions of 0.8 MMT CO₂ Eq. (842 kt of CO₂), CH₄ emissions of less than 0.05 MMT CO₂ Eq., and N₂O emissions of less than 0.05 MMT CO₂ Eq. The application of synthetic fertilizers to forest soils in 2014 resulted in N₂O emissions of 0.5 MMT CO₂ Eq. (2 kt of N₂O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455 percent since 1990, but still account for a relatively small portion of overall emissions. Additionally, N₂O emissions from fertilizer application to settlement soils in 2014 accounted for 2.4 MMT CO₂ Eq. (8 kt of N₂O). This represents an increase of 78 percent since 1990. Forest fires in 2014 resulted in CH₄ emissions of 7.3 MMT CO₂ Eq. (294 kt of N₂O), and N₂O emissions of 4.8 MMT CO₂ Eq. (16 kt of N₂O). Emissions and removals from LULUCF are summarized in Table 6-3 by land-use and category, and Table 6-4 and Table 6-5 by gas in MMT CO₂ Eq. and kt, respectively.

Table 6-2: Emissions from Land Use, Land-Use Change, and Forestry by Gas (MMT CO₂ Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
CO₂	8.1	9.0	9.6	8.9	11.0	9.0	9.5
Cropland Remaining Cropland: CO ₂							
Emissions from Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Cropland Remaining Cropland: CO ₂							
Emissions from Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
CH₄	3.3	9.9	3.3	6.6	11.1	7.3	7.4
Forest Land Remaining Forest Land:							
Non-CO ₂ Emissions from Forest Fires	3.3	9.9	3.3	6.6	11.1	7.3	7.3
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	3.6	9.3	5.0	7.3	10.3	7.7	7.7
Forest Land Remaining Forest Land:	2.2	6.5	2.2	4.4	7.3	4.8	4.8

Non-CO ₂ Emissions from Forest Fires							
Settlements Remaining Settlements:							
N ₂ O Fluxes from Settlement Soils ^a	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Forest Land Remaining Forest Land:							
N ₂ O Fluxes from Forest Soils ^b	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Wetlands Remaining Wetlands:							
Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions	15.0	28.2	17.8	22.9	32.3	24.1	24.6

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^b Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Totals may not sum due to independent rounding.

Table 6-3: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry by Land Use and Land-Use Change Category (MMT CO₂ Eq.)

Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Forest Land Remaining Forest Land	(718.0)	(675.0)	(736.2)	(725.2)	(717.1)	(726.5)	(729.7)
Changes in Forest Carbon Stock ^a	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Non-CO ₂ Emissions from Forest Fires	5.4	16.5	5.4	11.0	18.3	12.2	12.2
N ₂ O Fluxes from Forest Soils ^b	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Land Converted to Forest Land	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Changes in Forest Carbon Stock	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Cropland Remaining Cropland	(27.2)	(6.3)	10.3	(4.5)	(1.0)	(1.0)	0.2
Changes in Agricultural Carbon Stock ^c	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
CO ₂ Emissions from Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
CO ₂ Emissions from Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Land Converted to Cropland	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Changes in Agricultural Carbon Stock ^c	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Grassland Remaining Grassland	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Changes in Agricultural Carbon Stock ^c	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Land Converted to Grassland	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Changes in Agricultural Carbon Stock ^c	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Wetlands Remaining Wetlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Settlements Remaining Settlements	(59.0)	(78.2)	(83.8)	(84.8)	(85.8)	(87.1)	(88.2)
Changes in Carbon Stocks in Urban Trees	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
N ₂ O Fluxes from Settlement Soils ^d	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Other	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
LULUCF Emissions^e	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^f	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^g	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^b Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^c Estimates include C stock changes in all pools.

^d Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^e LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^f LULUCF Total Net Flux includes any C sequestration gains and losses from all land use and land use conversion categories.

^g The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Table 6-4: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry by Gas (MMT CO₂ Eq.)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO₂ Flux^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
Forest Land Remaining Forest Land ^b	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)
Land Converted to Forest Land	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Cropland Remaining Cropland	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)
Land Converted to Cropland	65.7	32.2	23.7	21.6	22.0	22.1	22.1
Grassland Remaining Grassland	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8
Land Converted to Grassland	39.1	43.1	39.3	39.9	40.4	40.4	40.4
Settlements Remaining Settlements	(60.4)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)	(90.6)
Other: Landfilled Yard Trimmings and Food Scraps	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)
CO₂	8.1	9.0	9.6	8.9	11.0	9.0	9.5
Cropland Remaining Cropland: CO ₂ Emissions from Urea Fertilization	2.4	3.5	3.8	4.1	4.2	4.3	4.5
Cropland Remaining Cropland: CO ₂ Emissions from Liming	4.7	4.3	4.8	3.9	6.0	3.9	4.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.1	1.1	1.0	0.9	0.8	0.8	0.8
CH₄	3.3	9.9	3.3	6.6	11.1	7.3	7.4
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	3.3	9.9	3.3	6.6	11.1	7.3	7.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	3.6	9.3	5.0	7.3	10.3	7.7	7.7
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	2.2	6.5	2.2	4.4	7.3	4.8	4.8
Settlements Remaining Settlements: N ₂ O Fluxes from Settlement Soils ^c	1.4	2.3	2.4	2.5	2.5	2.4	2.4
Forest Land Remaining Forest Land: N ₂ O Fluxes from Forest Soils ^d	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
LULUCF Emissions^e	15.0	28.2	17.8	22.9	32.3	24.1	24.6
LULUCF Total Net Flux^a	(753.0)	(726.7)	(784.3)	(784.9)	(782.0)	(783.7)	(787.0)
LULUCF Sector Total^f	(738.0)	(698.5)	(766.4)	(762.0)	(749.7)	(759.6)	(762.5)

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Net CO₂ flux 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, Settlements Remaining Settlements, and Other*.

^b Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^c Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^d Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

^e LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^f The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

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

Table 6-5: Emissions and Removals (Flux) from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2010	2011	2012	2013	2014
Net CO ₂ Flux ^a	(752,993)	(726,692)	(784,268)	(784,882)	(782,024)	(783,680)	(787,045)
Forest Land Remaining Forest Land ^b	(723,536)	(691,873)	(742,040)	(736,690)	(735,837)	(739,112)	(742,328)
Land Converted to Forest Land	(677)	(819)	(374)	(372)	(352)	(350)	(349)
Cropland Remaining Cropland	(34,326)	(14,116)	1,787	(12,484)	(11,179)	(9,273)	(8,428)
Land Converted to Cropland	65,710	32,168	23,695	21,601	22,048	22,097	22,104
Grassland Remaining Grassland	(12,865)	(3,254)	(7,315)	3,112	3,552	3,769	3,772
Land Converted to Grassland	39,083	43,087	39,308	39,859	40,358	40,380	40,383
Settlements Remaining Settlements	(60,408)	(80,523)	(86,129)	(87,250)	(88,372)	(89,493)	(90,614)
Other: Landfilled Yard Trimmings and Food Scraps	(25,975)	(11,360)	(13,200)	(12,659)	(12,242)	(11,698)	(11,585)
CO₂	8,139	8,955	9,584	8,898	11,015	9,021	9,495
Cropland Remaining Cropland: CO ₂ Emissions from Urea Fertilization	2,417	3,504	3,778	4,099	4,225	4,342	4,514
Cropland Remaining Cropland: CO ₂ Emissions from Liming	4,667	4,349	4,784	3,873	5,978	3,909	4,139
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,055	1,101	1,022	926	812	770	842
CH₄	131	397	131	265	443	294	294
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	131	397	131	265	443	294	294
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
N₂O	12	31	17	25	34	26	26
Forest Land Remaining Forest Land: Non-CO ₂ Emissions from Forest Fires	7	22	7	15	24	16	16
Settlements Remaining Settlements: N ₂ O Fluxes from Settlement Soils ^c	5	8	8	8	9	8	8
Forest Land Remaining Forest Land: N ₂ O Fluxes from Forest Soils ^d	+	2	2	2	2	2	2
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt

^a Net CO₂ flux 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*, *Settlements Remaining Settlements*, and *Other*.

^b Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^c Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^d Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emissions inventories, the gross emissions total presented in this report for the United States excludes emissions and sinks

from LULUCF. The net emissions total presented in this report for the United States includes emissions and sinks from LULUCF. All emissions and sinks estimates are calculated using internationally-accepted methods provided by the IPCC.⁶ Additionally, the calculated emissions and sinks 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.⁷ The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard, U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted.

6.1 Representation of the U.S. Land Base

A national land-use categorization 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 6-6), (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 6-7), and (3) account for greenhouse gas fluxes on all managed 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 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). The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible, and does allow for potentially subjective decisions in regards to subdividing natural and anthropogenic driven emissions. 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 U.S. land area into the thirty-six IPCC land-use and land-use change categories (Table 6-7) (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI)⁸ and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)⁹ Database. The Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD)¹⁰ is also used to identify land uses in regions that were not included in the NRI or FIA.

⁶ See <<http://www.ipcc-nngip.iges.or.jp/public/index.html>>.

⁷ See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

⁸ NRI data is available at <<http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>>.

⁹ FIA data is available at <<http://www.fia.fs.fed.us/tools-data/default.asp>>.

¹⁰ NLCD data is available at <<http://www.mrlc.gov/>> and MRLC is a consortium of several U.S. government agencies.

The total land area included in the U.S. Inventory is 936 million hectares across the 50 states.¹¹ Approximately 890 million hectares of this land base is considered managed and 46 million hectares is unmanaged, which has not changed by much over the time series of the Inventory (Table 6-7). In 2014, the United States had a total of 295 million hectares of managed Forest Land (3.2 percent increase since 1990), 164 million hectares of Cropland (6.3 percent decrease since 1990), 321 million hectares of managed Grassland (1.7 percent decrease since 1990), 42 million hectares of managed Wetlands (7.2 percent decrease since 1990), 43 million hectares of Settlements (28 percent increase since 1990), and 25 million hectares of managed Other Land (Table 6-7). Wetlands are not differentiated between managed and unmanaged, and are reported solely as managed. 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 (e.g., *Grassland Remaining Grassland*, interior Alaska).¹² Planned improvements are under development to account for C stock changes on all managed land (e.g., Grasslands and Forest Lands in Alaska) and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns, although all land uses occur within each of the 50 states (Table 6-6). Forest Land tends to be more common in the eastern 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. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-6: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land-Use Categories	1990	2005	2010	2011	2012	2013	2014
Managed Lands	890,019	890,016	890,017	890,017	890,017	890,017	890,017
Forest Land	285,837	292,106	294,175	294,585	294,988	294,988	294,988
Croplands	174,678	166,064	163,745	163,745	163,752	163,752	163,752
Grasslands	326,526	323,239	321,717	321,421	321,118	321,118	321,118
Settlements	33,420	40,450	42,645	42,645	42,648	42,648	42,648
Wetlands	45,361	43,004	42,336	42,223	42,113	42,112	42,113
Other Land	24,197	25,154	25,398	25,398	25,399	25,399	25,399
Unmanaged Lands	46,211	46,214	46,213	46,213	46,213	46,213	46,213
Forest Land	9,634	9,634	9,634	9,634	9,634	9,634	9,634
Croplands	0	0	0	0	0	0	0
Grasslands	25,782	25,782	25,782	25,782	25,782	25,782	25,782
Settlements	0	0	0	0	0	0	0
Wetlands	0	0	0	0	0	0	0
Other Land	10,795	10,797	10,797	10,797	10,797	10,797	10,797
Total Land Areas	936,230						
Forest Land	295,471	301,740	303,810	304,219	304,622	304,622	304,622
Croplands	174,678	166,064	163,745	163,745	163,752	163,752	163,752
Grasslands	352,308	349,021	347,499	347,203	346,900	346,900	346,900
Settlements	33,420	40,450	42,645	42,645	42,648	42,648	42,648
Wetlands	45,361	43,004	42,336	42,223	42,113	42,112	42,113
Other Land	34,992	35,951	36,195	36,195	36,196	36,196	36,196

¹¹ The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future reports.

¹² These “managed area” discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

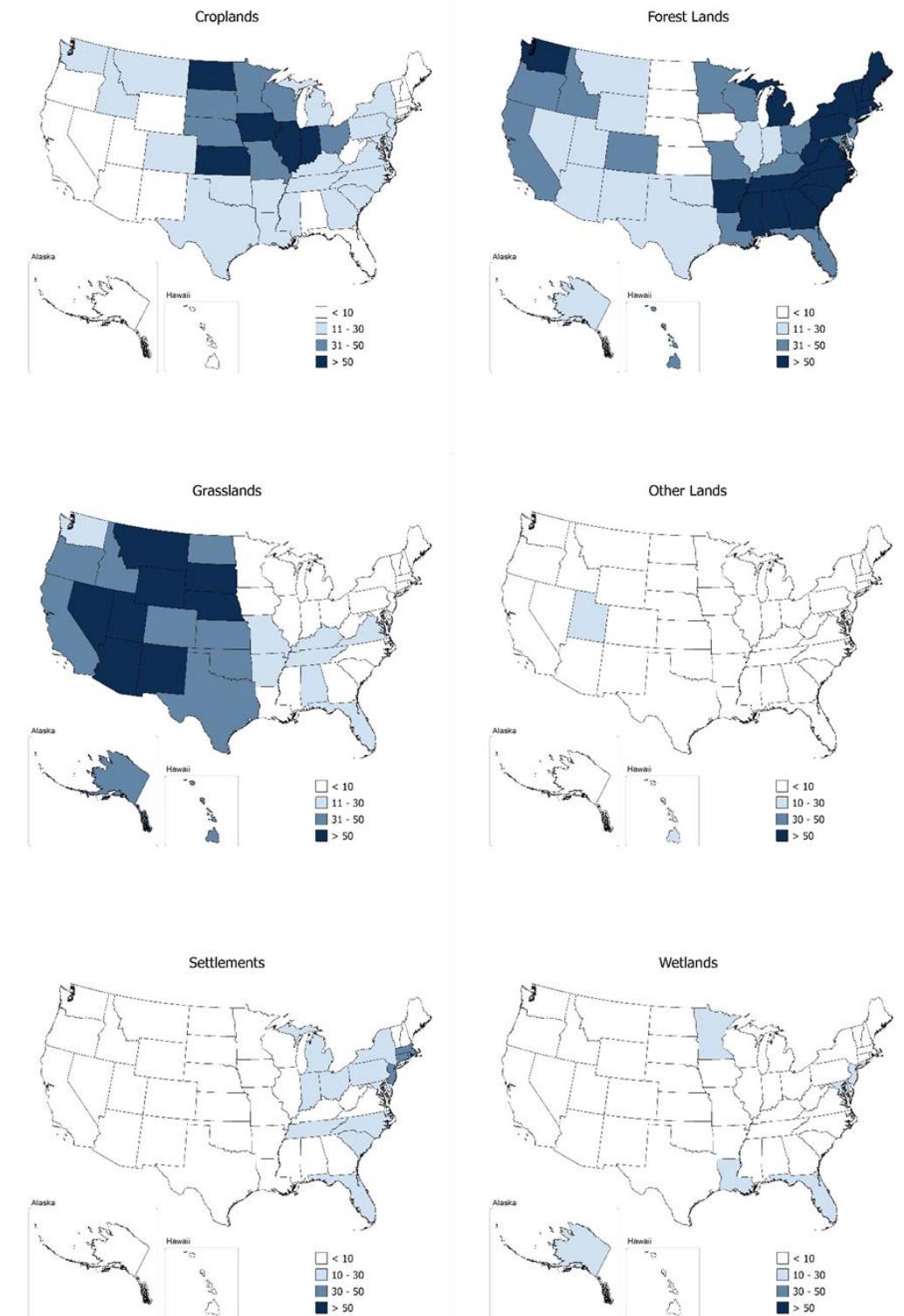
**Table 6-7: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States
(Thousands of Hectares)**

Land-Use & Land- Use Change Categories ^a	1990	2005	2010	2011	2012	2013	2014
Total Forest Land	285,837	292,106	294,175	294,585	294,988	294,988	294,988
FF	284,642	291,098	293,234	293,644	294,051	294,051	294,051
CF	233	215	189	189	183	183	183
GF	841	635	637	637	638	638	638
WF	20	23	23	23	23	23	23
SF	15	15	16	16	15	15	15
OF	86	120	77	77	77	77	77
Total Cropland	174,678	166,064	163,745	163,745	163,752	163,752	163,752
CC	161,960	151,903	152,079	152,079	152,084	152,084	152,084
FC	252	91	48	48	49	49	49
GC	12,066	13,581	11,215	11,215	11,215	11,215	11,215
WC	141	166	114	114	114	114	114
SC	77	78	72	72	72	72	72
OC	182	245	217	217	217	217	217
Total Grassland	326,526	323,239	321,717	321,421	321,118	321,118	321,118
GG	316,489	303,987	303,284	302,989	302,687	302,688	302,687
FG	899	1,538	1,481	1,481	1,479	1,479	1,479
CG	8,396	16,335	15,776	15,776	15,776	15,776	15,776
WG	283	437	250	250	250	250	250
SG	53	115	119	119	119	119	119
OG	406	827	806	806	806	806	806
Total Wetlands	45,361	43,004	42,336	42,223	42,113	42,112	42,113
WW	44,649	41,785	41,280	41,167	41,056	41,056	41,056
FW	38	41	35	35	35	35	35
CW	214	362	321	321	321	321	321
GW	396	770	661	661	661	661	661
SW	2	1	2	2	2	2	2
OW	63	45	38	38	38	38	38
Total Settlements	33,420	40,450	42,645	42,645	42,648	42,648	42,648
SS	30,632	32,188	34,870	34,870	34,870	34,870	34,870
FS	232	339	362	362	365	365	365
CS	1,227	3,530	3,205	3,205	3,205	3,205	3,205
GS	1,268	4,164	3,981	3,981	3,981	3,981	3,981
WS	6	26	24	24	24	24	24
OS	55	201	204	204	204	204	204
Total Other Land	24,197	25,154	25,398	25,398	25,399	25,399	25,399
OO	23,162	23,312	23,475	23,475	23,476	23,476	23,476
FO	37	54	61	61	61	61	61
CO	328	706	812	812	812	812	812
GO	531	966	969	969	969	969	969
WO	135	109	70	70	70	70	70
SO	4	7	12	12	12	12	12
Grand Total	890,019	890,016	890,017	890,017	890,017	890,017	890,017

^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*).

Note: 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.

Figure 6-1: Percent of Total Land Area for Each State in the General Land-Use Categories for 2014



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 location data on all parcels of land. Approach 3 extends Approach 2 by providing location data on all parcels of land, such as maps, along with the land-use history. 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 and FIA are Approach 2 data sources that do not provide spatially-explicit representations of land use and land-use conversions, even though land use and land-use conversions are tracked explicitly at the survey locations. NRI and FIA data are aggregated and used to develop a land-use conversion matrix for a political or ecologically-defined region. NLCD is a spatially-explicit time series of land-cover data that is used to inform the classification of land use, and is therefore Approach 3 data. 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 basic IPCC (2006) definition of managed land, 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

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 by use within the NRI. Therefore, unless wetlands are managed for 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, all Wetlands are reported as managed. See the Planned Improvements section of the Inventory for work being done to refine the Wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO₂ 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.

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 centimeters) 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 hay or 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-asides¹⁸) 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 pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Grassland may have three or fewer years of

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 <<http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home>>.

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.

hay production¹⁹ that is otherwise pasture or rangelands. 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 and shrubs, such as mesquite, chaparral, mountain shrub, 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 silvipasture and windbreaks, if the land is principally grasses, 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 the areas of 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, including Cropland (drained wetlands for crop production and also systems that are flooded for most or just part of the year, such as rice cultivation and cranberry production), Grassland (drained wetlands dominated by grass cover), and Forest Land (including drained or un-drained forested wetlands).
- *Settlements:* A land-use category representing developed areas consisting of units of 0.25 acres (0.1 ha) or more 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 tracts of less than 10 acres (4.05 ha) that may meet the definitions for Forest Land, 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, which allows the total of identified land areas to match the managed land base. Following the guidance provided by the IPCC (2006), C stock changes and non-CO₂ 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-CO₂ 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 6-8). 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 the surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data from which to estimate C stock changes on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

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.

²⁰ 2006 IPCC Guidelines do not include provisions to separate desert and tundra as land-use categories.

Table 6-8: 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			
<i>Non-Federal</i>		•	
<i>Federal</i>	•		
Hawaii			
<i>Non-Federal</i>	•		
<i>Federal</i>		•	
Alaska			
<i>Non-Federal</i>		•	
<i>Federal</i>		•	
Croplands, Grasslands, Other Lands, Settlements, and Wetlands			
Conterminous United States			
<i>Non-Federal</i>	•		
<i>Federal</i>		•	
Hawaii			
<i>Non-Federal</i>	•		
<i>Federal</i>		•	
Alaska			
<i>Non-Federal</i>		•	
<i>Federal</i>		•	

National Resources Inventory

For the Inventory, the NRI is the official source of data on all land uses on non-federal lands in the conterminous United States and Hawaii (except Forest Land), and is also used as the resource 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, 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 2010 from the NRI. The land use patterns are assumed to remain the same from 2010 through 2014 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 another statistically-based survey for the conterminous United States, and the official source of data on Forest Land area and management data for the Inventory in this region of the country. 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 FIA about ten years ago. Most states, though, have only recently been brought into this system. 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 years. 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 2012 through 2014; see Table A-255).

National Land Cover Dataset

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 a portion of Alaska.²¹ Consequently, major gaps exist in the land use classification 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 as a supplementary database 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.

NLCD products provide land-cover for 1992, 2001, 2006, and 2011 in the conterminous United States (Homer et al. 2007), and also for Alaska and Hawaii in 2001. For the conterminous United States, the NLCD data have been further processed to derive Land Cover Change Products for 2001, 2006, and 2011 (Fry et al. 2011, Homer et al. 2007, Jin et al. 2013). A change product is not available for Alaska and Hawaii because the 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 contain 21 categories of land-cover information, which have been aggregated into the 36 IPCC land-use categories for the conterminous United States and into the 6 IPCC land-use categories for Hawaii and Alaska.

The aggregated maps of IPCC land-use categories were used in combination with the NRI database to represent land use and land-use change for federal lands, as well as federal and non-federal lands in Alaska. 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 is the NRI). NLCD is strictly a source of land-cover information, however, and does not provide the necessary site conditions, crop types, and management information from which to estimate C stock changes on those lands. The sources of these additional data are discussed in subsequent sections of the NIR.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. In order to apply the definition in an analysis of managed land, the following criteria are used:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land or Other Lands may be designated as unmanaged land;
- All Forest Lands with active fire protection are considered managed;
- All Grassland is considered managed at a county scale if there are livestock in the county;²³
- 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 private organizations);
- Lands with active and/or past resource extraction are considered managed; and

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 FIA and NRI survey programs also do not include U.S. Territories with the exception of non-federal lands in Puerto Rico, which are included in the NRI survey. Furthermore, NLCD does not include coverage for all U.S. Territories.

²³ Assuming all Grasslands are grazed in a county with even very small livestock populations is a conservative assumption about human impacts on Grasslands. Currently, detailed information on grazing at sub-county scales is not available for the United States to make a finer delineation of managed land.

- 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 is conducted using a geographic information system. Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Jin et al. 2013). 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. The designation of grasslands as managed is based on livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2014). 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 permit 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 approximately 130 petroleum extraction sites and 223 mines. 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. The remaining land represents the unmanaged land base. The resulting spatial product is used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii, in addition to determining which areas in the NLCD for Alaska are included in the managed land base.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the thirty-six IPCC land-use/land-use conversion categories using definitions developed to meet national circumstances, while adhering to IPCC (2006).²⁴ In practice, the land was initially classified into a variety of land-use categories within the NRI, FIA, and NLCD datasets, and then aggregated into the thirty-six 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 estimating Forest Land in the conterminous United States.

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 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 and Wetlands). All adjustments are made at the state scale to address the differences in Forest Land definitions and the resulting discrepancies in areas among the land use and land-use change categories. There

²⁴ Definitions are provided in the previous section.

are three steps in this process. The first step involves adjustments for *Land Converted to Forest Land* (Grassland, Cropland and Wetlands), followed by adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland and Wetlands), and finally adjustments to *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 do not provide specific land-use categories that are converted to Forest Land, but rather a sum of all *Land Converted to Forest Land*. The NRI and NLCD provide information on specific land use conversions, however, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of land use change into Forest Land for the state, prior to any adjustments. For example, if 50 percent of 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 does not provide information on the specific land-use changes, and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount 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, in order to balance the change in *Forest Land Remaining Forest Land* area, and ensure 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. (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 solely on the NLCD data (Table 6-8). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.²⁵

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land:* Both non-federal and federal forest lands in the conterminous United States and coastal Alaska are covered by 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. FIA does have survey plots in coastal Alaska that are used to determine the C stock changes, but the area data for this region are based on the 2001 NLCD. In addition, interior Alaska is not currently surveyed by FIA so forest land in this region are also based on the 2001 NLCD. NRI is being 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 will be collected in Hawaii in the future.
- *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

²⁵ Only one year of data are currently available for Alaska so there is no information on land-use change for this state.

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 fluxes 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 lands 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 federal wetlands and wetlands in Alaska are covered by the NLCD.²⁶
- *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 acre (4.05 ha) threshold and are Grassland, they will be classified as such by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Settlements on federal lands and in Alaska are covered by 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, in the following manner:

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 will be 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 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 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. 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 cranberries, 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 from these areas are included in the Inventory if the land is considered managed and presumably impacted by anthropogenic activity in accordance with the guidance provided in IPCC (2006).

²⁶ This analysis does not distinguish between managed and unmanaged wetlands, which is a planned improvement for the Inventory.

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 U.S. Census Bureau gathers data on the U.S. population and economy, and has a database of land areas for the country. The land area estimates from the U.S. Census Bureau differ from those provided by the land-use surveys used in the Inventory because of discrepancies in the reporting approach for the Census and the methods used in the NRI, FIA, and NLCD. 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 U.S. Census Survey. More importantly, the U.S. Census Survey does not provide a time series of land-use change data or land management information. Consequently, the U.S. Census Survey was not adopted as the official land area estimate for the Inventory. Rather, the NRI, FIA, and NLCD datasets were adopted because these databases provide full coverage of land area and land use for the conterminous United States, Alaska, and Hawaii, in addition to management and other data relevant for the Inventory. Regardless, the total difference between the U.S. Census Survey and the combined NRI, FIA, and NLCD data is about 46 million hectares for the total U.S. land base of about 936 million hectares currently included in the Inventory, or a 5 percent difference. 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 U.S. 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.

Recalculations Discussion

In previous years, FIA did not separate Forest Land into land use and land use change categories, reporting all areas as *Forest Land Remaining Forest Land* for the purpose of estimating forest carbon stock changes. In this Inventory, forest carbon stock changes are reported for *Land Converted to Forest*, *Forest Converted to other Land Uses*, in addition to *Forest Land Remaining Forest Land*. As such, adjustments to NRI and NLCD accounted for land use changes associated with Forest Land, which led to minor adjustments to the time series. Other small changes occurred in the areas of Grassland, Wetland, and Cropland due to the modifications to the Forest Land data in FIA and the process of combining the NRI, NLCD and FIA products into a harmonized dataset.

In addition to the changes in the FIA data, a new NRI dataset was incorporated into the current Inventory extending the time series from 2007 to 2010. The NRI program also recalculated the previous time series based on changes to the classification and imputation procedures for filling gaps.

The definition of Grassland also changed so that a land use history that includes three or fewer years within a sequence of grass pasture or rangeland is considered Grassland, rather than converting these areas into Cropland. Land use remains virtually unchanged in these cases with harvesting of the existing grass vegetation, with no impact on carbon stocks. In contrast, longer term adoption of continuous hay tends to change the management to a more intensive set of practices that influences the carbon stocks. This exception is only applied to hay. Any change in land management that involves cultivation of other crops, such as corn, wheat, or soybeans, is still considered a land use change.

The revisions in land representation led to the following changes in land use areas for the managed land base: on average over the time series, Forest Land area decreased by 0.2 percent, Cropland area increased by 3.1 percent, Grassland area increased by 0.7 percent, Wetland area decreased by 0.8 percent, Settlements decreased by 16.6 percent, and Other Lands increased by 5.8 percent.

Planned Improvements

A key planned improvement is to fully incorporate area data by land-use type for U.S. Territories into the Inventory. Fortunately, most of the managed land in the United States is included in the current land-use statistics, but a complete accounting 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: Preliminary Estimates of Land Use in U.S. Territories.

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 a land-cover product 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.

Table 6-9: 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
Forest Land	404,004	13,107	24,650	25,761	15,440
Grasslands	299,714	12,148	15,449	13,636	1,830
Other Land	5,502	1,006	1,141	5,186	298
Settlements	130,330	7,650	11,146	3,637	1,734
Wetlands	24,525	4,748	1,633	260	87
Total	883,788	38,796	54,255	48,769	19,777
					1,045,385

Additional work will be conducted to reconcile differences in Forest Land estimates between the NRI and FIA. This improvement will include an analysis designed to develop finer scale adjustments at the survey locations. Harmonization is planned at the survey location scale using ancillary data, such as the NLCD, which is expected to better capture the differences in Forest Land classification between the two surveys, as well as the conversions of land to other uses that involve Forest Land.

NLCD data for Alaska were recently released for 2011, and will be used to analyze land use change for this state in the next Inventory. There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990, 2000, and 2010 U.S. Census data). Using the population statistics, “urban clusters” are defined as areas with more than 500 people per square mile. The USFS is currently moving ahead with an Urban Forest Inventory program so that urban forest area estimates will be consistent with FIA forest area estimates outside of urban areas, which would be expected to reduce omissions and overlap of forest area estimates along urban boundary areas.

As adopted by the UNFCCC, new guidance in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* will be implemented in the Inventory. This will likely have implications for the classification of managed and unmanaged wetlands in the Inventory report. More detailed wetlands datasets will also be evaluated and integrated into the analysis in order to implement the new guidance.

6.2 Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source 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 the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 centimeters (cm) at transect intersection, lying on the ground.
- 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 to account for 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 CO₂ in the case of decomposition and as CO₂, CH₄, N₂O, CO, 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 accounted for under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the harvested timber 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 CH₄ from wood in SWDS which is included in the Waste sector, are also accounted for under 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 forest C pools and two harvested wood pools. The underlying methodology for determining C stock and stock-change relies on data

from the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual forest inventory system is implemented across all U.S. forest lands within the conterminous 48 states but excluding interior Alaska, Hawaii, and U.S. Territories at this time. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the C estimates (Woodall et al. 2015a). The net change in C stocks for each pool is estimated, and then the changes in stocks are summed for all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Changes in C stocks from disturbances, such as forest fires or harvesting, are included in the net changes. For instance, an inventory conducted after fire counts only the trees that are left. Therefore, changes in C stocks from natural disturbances, such as wildfires, pest outbreaks, and storms, are accounted for in the forest inventory approach; however, they are highly variable from year to year. 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 forest lands that have been forest lands for 20 years or longer and the latter being lands that have been classified as forest lands for less than 20 years. This is the first report to delineate forest C stock changes by these two categories and in order to facilitate this delineation, a different approach to forest C accounting was used this year in the United States (Woodall et al. 2015a).

Forest Area in the United States

Approximately 34 percent of the U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in the Section 6.1 Representation of the U.S. Land Base. The most recent forest inventories from each of the conterminous 48 states (USDA Forest Service 2014a, 2014b) comprise an estimated 266 million hectares of forest land that are considered managed and are included in this Inventory. An additional 6.2 million hectares of forest land in southeast and south central coastal Alaska are inventoried and are also included here. Some differences exist in forest land defined in Oswalt et al. (2014) and the forest land included in this report, which is based on the USDA Forest Service (2015b) forest inventory. Annual inventory data are not yet available for Hawaii and interior Alaska, but estimates of these areas are included in Oswalt et al. (2014). Updated survey data for central and western forest land in both Oklahoma and Texas have only recently become available, and these forests contribute to overall C stocks reported below. While Hawaii and U.S. Territories have relatively small areas of forest land and thus may not substantially influence the overall C budget, these regions will be added to the forest C estimates as sufficient data become available. Agroforestry systems that meet the definition of forest land are also not currently accounted for in the Inventory since they are not explicitly inventoried by either the FIA program or the Natural Resources Inventory (NRI)²⁷ of the USDA Natural Resources Conservation Service (Perry et al. 2005).

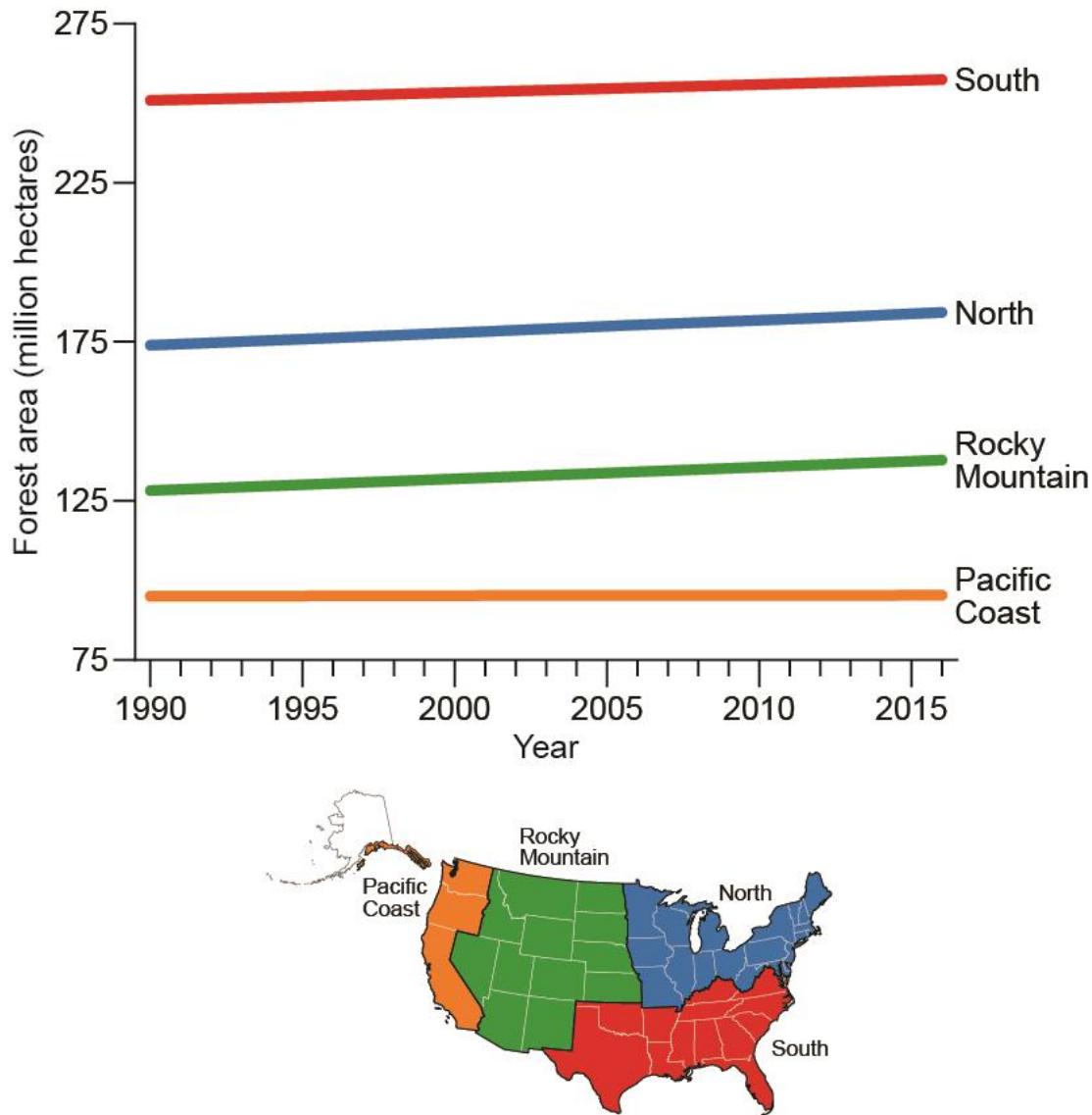
An estimated 77 percent (211 million hectares) of U.S. forests in southeast and southcentral coastal Alaska and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Ten percent of southeast and southcentral coastal Alaska forest land and 80 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 69 million hectares are lower productivity forest lands (Oswalt et al. 2014). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than forest land not meeting the minimum level of productivity and removed from production.

Since the late 1980s, forest land area in southeast and southcentral coastal Alaska and the conterminous United States has increased by about 14 million hectares (Oswalt et al. 2014) with the southern region of the United States containing the most forest land (Figure 6-2). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Current trends in the forest land area in the conterminous U.S. and southeast and south central coastal Alaska represented here show an average annual rate of increase of 0.1 percent. In addition to the increase in forest area, the major influences to the net C flux from forest land across the 1990 to 2014 time series are management activities and the ongoing impacts of 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

²⁷ The Natural Resources Inventory of the USDA Natural Resources Conservation Service is described in the Section 6.1—Representation of the U.S. Land Base.

growth of aboveground biomass (and possible changes to the other C pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C in the aboveground biomass pool.²⁸ 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 the conterminous U.S. states is about double the volume of annual removals on timberlands (Oswalt et al. 2014). 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.

Figure 6-2: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and coastal Alaska (1990-2014, Million Hectares)



Forest Carbon Stocks and Stock Change

In the United States, improved forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2014. The rate of forest clearing in the 17th century following European settlement

²⁸ The term “biomass density” refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Dry biomass is assumed to be 50 percent C by weight.

had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested 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 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). The size of the stocks in these long-term C storage pools has increased during the last century with the question arising as to how long U.S. forest land can remain a net C sink (Coulston et al. 2015; Wear and Coulston 2015). Changes in C stocks in the forest and harvested wood pools associated with *Forest Land Remaining Forest Land* were estimated to account for net sequestration of 742.3 MMT CO₂ Eq. (202.5 MMT C) in 2014 (Table 6-10 and Table 6-11). Overall, estimates of average C density in forest ecosystems (including all pools) remained stable at approximately 0.0003 MMT C ha⁻¹ from 1990 to 2014 (Table 6-11 and Table 6-12). The stable forest ecosystem C density when combined with increasing forest area results in net C accumulation over time. Management practices that increase C stocks on forest land, as well as legacy effects of afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land area in the United States (Woodall et al. 2015b). 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). Aboveground live biomass accounted for the majority of net sequestration among all forest ecosystem pools (Figure 6-4).

The estimated net sequestration of C in HWP was 112.3 MMT CO₂ Eq. (30.6 MMT C) in 2014 (Table 6-10 and Table 6-11). The majority of this sequestration, 69.5 MMT CO₂ Eq. (19.0 MMT C) was from wood and paper in SWDS. Products in use accounted for an estimated 42.7 MMT CO₂ Eq. (11.7 MMT C) in 2014.

Table 6-10: Net CO₂ Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools. (MMT CO₂ Eq.)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Forest	(598.8)	(584.3)	(647.2)	(637.8)	(632.4)	(631.2)	(630.1)
Aboveground	(312.4)	(310.3)	(331.2)	(329.4)	(324.6)	(323.5)	(322.5)
Belowground	(66.6)	(65.7)	(69.6)	(69.3)	(68.2)	(67.9)	(67.6)
Dead Wood	(34.8)	(44.0)	(50.2)	(52.9)	(53.7)	(53.9)	(54.2)
Litter	(35.9)	(28.5)	(34.5)	(33.9)	(33.1)	(32.9)	(32.7)
Soil Organic C	(149.2)	(135.8)	(161.7)	(152.4)	(152.8)	(152.9)	(153.1)
Harvested Wood	(124.7)	(107.6)	(94.8)	(98.9)	(103.4)	(107.9)	(112.3)
Products in Use	(55.6)	(44.2)	(30.4)	(33.1)	(36.4)	(39.6)	(42.7)
SWDS	(69.1)	(63.4)	(64.5)	(65.8)	(67.1)	(68.3)	(69.5)
Total Net Flux	(723.5)	(691.9)	(742.0)	(736.7)	(735.8)	(739.1)	(742.3)

Note: Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed forests in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (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.

Table 6-11: Net C Flux from Forest Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Forest	(163.3)	(159.3)	(176.5)	(173.9)	(172.5)	(172.2)	(171.8)
Aboveground Biomass	(85.2)	(84.6)	(90.3)	(89.8)	(88.5)	(88.2)	(88.0)
Belowground Biomass	(18.2)	(17.9)	(19.0)	(18.9)	(18.6)	(18.5)	(18.4)
Dead Wood	(9.5)	(12.0)	(13.7)	(14.4)	(14.6)	(14.7)	(14.8)
Litter	(9.8)	(7.8)	(9.4)	(9.3)	(9.0)	(9.0)	(8.9)
Soil Organic C	(40.7)	(37.0)	(44.1)	(41.6)	(41.7)	(41.7)	(41.7)

Harvested Wood	(34.0)	(29.3)	(25.9)	(27.0)	(28.2)	(29.4)	(30.6)
Products in Use	(15.2)	(12.1)	(8.3)	(9.0)	(9.9)	(10.8)	(11.7)
SWDS	(18.8)	(17.3)	(17.6)	(17.9)	(18.3)	(18.6)	(19.0)
Total Net Flux	(197.3)	(188.7)	(202.4)	(200.9)	(200.7)	(201.6)	(202.5)

Note: Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a portion of managed lands in Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Parentheses indicate net C sequestration (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.

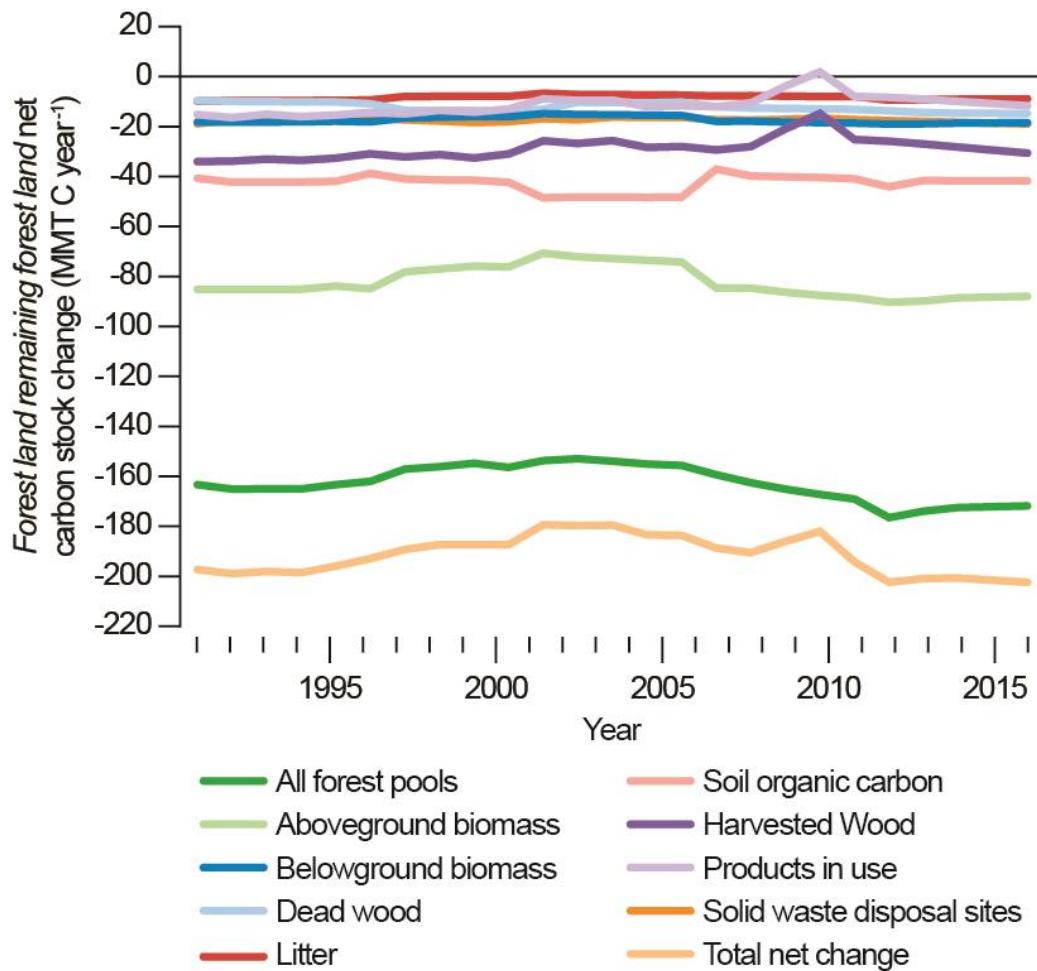
Stock estimates for forest and harvested wood C storage pools are presented in Table 6-12. Together, the estimated aboveground biomass and soil C pools account for a large proportion of total forest C stocks. Note that the forest land area estimates in Table 6-12 do not precisely match those in Section 6.1 Representation of the U.S. Land Base for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-12 only include managed forest land in the conterminous 48 states and southeast and south central coastal Alaska (which is the current area encompassed by FIA survey data, approximately 6.2 million ha) while the estimates in Section 6.1 include all managed forest land in Alaska (approximately 28.0 million ha as part of interior Alaska).

Table 6-12: Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	2005	2010	2011	2012	2013	2014	2015
Forest Area (1000 ha)	261,796	268,029	270,065	270,462	270,871	271,871	271,719	272,158
Carbon Pools (MMT C)								
Forest	84,891	87,271	88,094	88,271	88,445	88,617	88,789	88,961
Aboveground Biomass	11,896	13,076	13,508	13,598	13,688	13,777	13,865	13,953
Belowground Biomass	2,442	2,691	2,782	2,801	2,820	2,839	2,857	2,876
Dead Wood	2,404	2,574	2,637	2,651	2,665	2,680	2,695	2,710
Litter	5,833	5,958	5,997	6,006	6,016	6,025	6,034	6,042
Soil Organic C	62,316	62,972	63,170	63,214	63,255	63,297	63,339	63,381
Harvested Wood	1,897	2,356	2,474	2,500	2,527	2,555	2,584	2,615
Products in Use	1,250	1,449	1,482	1,490	1,499	1,509	1,520	1,531
SWDS	647	906	992	1,010	1,028	1,046	1,065	1,084
Total C Stock	86,788	89,627	90,568	90,771	90,972	91,172	91,374	91,576

Note: Forest area and C stock estimates include all *Forest Land Remaining Forest Land* in the conterminous 48 states and southeast and south central coastal Alaska (6.2 million ha), which is the current area encompassed by FIA survey data. Forest C stocks do not include forest stocks in U.S. Territories, Hawaii, a large portion of interior Alaska (28.0 million ha), or trees on non-forest land (e.g., urban trees, agroforestry systems). The forest area estimates in this table do not match those Section 6.1 Representation of the U.S. Land Base, which includes all managed forest land in Alaska. 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. Inventories 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 2014 requires estimates of C stocks for 2014 and 2015.

Figure 6-3: Estimated Net Annual Changes in C Stocks for Major C Pools in Forest Land Remaining Forest Land in the Conterminous U.S. and Coastal Alaska (MMT C year⁻¹)



Box 6-3: CO₂ Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for 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 account for CO₂ emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska that are captured in this Inventory. Because it is of interest to quantify the magnitude of CO₂ emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO₂ estimates are based on the same methodology as applied for the non-CO₂ 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 and a combination of U.S.-specific data on annual area burned and potential fuel availability together with default combustion factors were employed to estimate CO₂ emissions from forest fires. CO₂ emissions for wildfires in the conterminous 48 states and in Alaska as well as prescribed fires in 2014 were estimated to be 92.3 MMT CO₂ year⁻¹ (Table 6-13). Most of this quantity is an embedded component of the net annual forest C stock change estimates provided previously (e.g., Table 6-11), but this separate approach to estimate emissions is necessary in order to associate a portion of emissions, including estimates of CH₄ and N₂O, with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that the estimates for Alaska provided

in Table 6-13 include all managed forest land in the state and are not limited to the subset with permanent inventory plots on managed lands as specified elsewhere in this chapter (e.g., Table 6-11).

Table 6-13: Estimates of CO₂ (MMT year⁻¹) Emissions from Forest Fires in the Conterminous 48 States and Alaska^a

Year	CO ₂ emitted from Wildfires in the Conterminous 48 States (MMT yr ⁻¹)	CO ₂ emitted from Wildfires in Alaska (MMTyr ⁻¹)	CO ₂ emitted from Prescribed Fires (MMTyr ⁻¹)	Total CO ₂ emitted (MMTyr ⁻¹)
1990	21.3	19.5	0.2	40.9
2005	42.9	80.7	1.3	124.9
2010	12.2	11.2	18.4	41.7
2011	73.9	3.5	5.9	83.3
2012	133.7	2.7	2.9	139.3
2013	64.7	22.3	5.3	92.3
2014 ^b	64.7	22.3	5.3	92.3

^a These emissions have already been accounted for in the estimates of net annual changes in C stocks, which account for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

^b The data for 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Methodology and Data Sources

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, 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. Harvested wood C 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 or harvested wood products is provided here. See Annex 3.13 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

The U.S. used a different accounting approach (Woodall et al. 2015a) for this Inventory than what was used in previous submissions that removes the older, often inconsistent inventory information from the accounting 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 include 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 inventory system does not extend into the 1990s, necessitating the adoption of a system to “backcast” the annual C estimates. To facilitate the backcasting of the U.S. annual forest inventory C estimates, the accounting framework used in this Inventory is 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 sequestration, forest aging, and disturbance effects (i.e., 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 (e.g., 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 nonforest observations in the FIA national database (U.S. Forest Service 2015a, b, c). Model predictions for before

the annual inventory period are constructed from the accounting framework using the annual observations. The accounting approach used this year is fundamentally driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; USDA Forest Service 2015d, 2015a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m² 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 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 framework was 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 2015d). Forest C calculations 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 U.S. (USDA Forest Service 2015b, 2015c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Tier 3 methods, as outlined by IPCC (2006), were used for the five reporting pools.

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, 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, which is 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 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.

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 accounting framework.

Carbon in Forest Soil

Soil organic carbon (SOC) is the largest terrestrial C sink, and management of this pool is a critical component of efforts to mitigate atmospheric C concentrations. SOC also affects essential biological, chemical, and physical soil functions such as nutrient cycling, water retention, and soil structure (Jandl et al. 2014). Much of the SOC on earth is found in forest ecosystems and is thought to be relatively stable. However, there is growing evidence that SOC is sensitive to global change effects, particularly land use histories, resource management, and climate. In the U.S., SOC in forests is monitored by the FIA program (O'Neill et al. 2005). In previous C inventory submissions, SOC predictions were based, in part, on a model using the State Soil Geographic (STATSGO) database compiled by the Natural Resources Conservation Service (NRCS) (Amichev and Glabraith 2004). Estimates of forest SOC found in the STATSGO database may be based on expert opinion rather than actual measurements. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of SOC measurement data on forest land in the conterminous U.S. and coastal Alaska (O'Neill et al. 2005). More than 5,000 profile observations of SOC on forest land from FIA and the International Soil Carbon Monitoring Network were used to develop and implement an approach that enabled the prediction of 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 SOC stocks and stock changes specific to forest land in the United States (Domke et al. In prep). Note that SOC is reported to a depth of 100 cm for Forest Land Remaining Forest Land to remain consistent with past reporting, however for consistency across land-use categories it is reported to a depth of 30 cm in Section 6.3 *Land Converted to Forest Land*.

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 and the U.S. forest products module (Ince et al. 2011). 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 accounting 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 U.S. used the production accounting 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. Annual estimates of change were calculated by tracking the 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. Emissions from HWP associated with wood biomass energy are not included in this accounting—a net of zero sequestration and emissions as they are a part of energy accounting (see Chapter 3).

Solidwood products added to pools 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 that additions of softwood lumber to housing 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, forthcoming). Estimates for disposal of products reflected 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.

The annual HWP variables that were used to estimate HWP contribution using the production approach are:

- (1) annual change of C in wood and paper products in use in the U.S. and other countries where the wood came from trees harvested in the United States, and
- (2) annual change of C in wood and paper products in SWDS in the U.S. and other countries where the wood came from trees harvested in the United States

The sum of these variables yield estimates for HWP contribution under the production accounting approach.

Uncertainty and Time-Series Consistency

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO₂ flux (IPCC Approach 1). A

Monte Carlo Stochastic Simulation of the Methods described above and probabilistic sampling of C conversion factors were used to determine the HWP uncertainty (IPCC Approach 2). See Annex 3.13 for additional information. The 2014 net annual change for forest C stocks was estimated to be between -1,018.4 and -465.7 MMT CO₂ Eq. around a central estimate of -742.3 MMT CO₂ Eq. at a 95 percent confidence level. This includes a range of -905.0 to -355.1 MMT CO₂ Eq. around a central estimate of -630.1 MMT CO₂ Eq. for forest ecosystems and -136.8 to -82.2 MMT CO₂ Eq. around a central estimate of -112.3 for HWP.

Table 6-14: 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	2014 Flux Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest C Pools ^a	CO ₂	(630.1)	(905.0)	(355.1)	-43.6%	43.6%
Harvested Wood Products ^b	CO ₂	(112.3)	(136.8)	(82.2)	-21.9%	26.8%
Total Forest	CO₂	(742.3)	(1,018.4)	(465.7)	-37.2%	37.3%

^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.

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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 2015d).

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. (2014) or selected population estimates generated from FIADB 6.0, which are available at an FIA internet site (USDA Forest Service 2015b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used. Finally, C stock estimates were compared with previous Inventory report estimates to ensure that any differences could be explained by either new data or revised calculation methods (see the Recalculations discussion, below).

Estimates of the HWP variables and the HWP contribution under the production accounting approach use data from U.S. Census and USDA Forest Service surveys of production and trade. Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources. 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

Forest ecosystem stock and stock-change estimates differ from the previous Inventory report principally due to the adoption of a new accounting framework (Woodall et al. 2015a). The major differences between the framework used this year and past accounting approaches is the sole use of annual FIA data and the back-casting of forest C stocks across the 1990s based on forest C stock density and land use change information obtained from the nationally consistent annual forest inventory coupled with in situ observations of non-tree C pools such as soils, dead wood, and litter. The use of this accounting framework has enabled the creation of the two land use sections for forest C stocks: *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. In prior submissions (e.g., the 1990 through 2013 Inventory submission), the C stock changes from *Land Converted to Forest Land* were a part of the *Forest Land Remaining Forest Land* section and it was not possible to disaggregate the estimates. A second major change was the adoption of a new approach to estimate forest soil C, the largest C stock in the U.S. For detailed discussion of these new approaches please refer to the Methodology section, Annex 3.13, Domke et al. (In prep), and Woodall et al. (2015a). In addition to these major changes, the refined land representation analysis described in Section 6.1 Representation of the U.S. Land Base which identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of “managed” land for these forest lands included in the FIA database. Therefore, the C stock and flux estimates for southeast and south central coastal Alaska, as included here, reflect that adjustment, which effectively reduces the managed forest area by approximately 5 percent.

In addition to the creation of explicit estimates of removals and emissions by *Forest Land Remaining Forest Land* versus *Land Converted to Forest Land*, the accounting framework used this year eliminated the use of periodic data (which may be inconsistent with annual inventory data) which contributed to a data artifact in prior estimates of emissions/removals from 1990 to the present. In the previous Inventory report, there was a reduction in net sequestration from 1995 to 2000 followed by an increase in net sequestration from 2000 to 2004. This artifact of comparing inconsistent inventories of the 1980s through 1990s to the nationally consistent inventories of the 2000s has been removed in this Inventory.

Estimated annual net additions to HWP C stocks increased slightly between 2014 and 2015. Estimated net additions to solidwood products in use slightly increased due to a further recovery of the housing market. Estimated net additions to products in use for 2014 are about 20 percent of the level of net additions to products in use in 2006, i.e., prior to the recession. The decline in net additions to HWP C stocks continued through 2008 from the recent high point in 2005. This is due to sharp declines in U.S. production of solidwood and paper products in 2007 and 2008 primarily due to the decline in housing construction. The low level of gross additions to solidwood and paper products in use in 2007 and 2008 were exceeded by discards from uses. The result is a net reduction in the amount of HWP C that is held in products in use during this time period. For 2008, emissions from landfills exceeded additions to landfills. That said, following the recent recession the net additions to landfills have returned to normal levels. Overall, there were net C additions to HWP in use and in SWDS combined due, in large part, to updated data on products in use from 2010 to the present.

Planned Improvements

Reliable estimates of forest C across the diverse ecosystems of the U.S. 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 accounting system, individual C pool estimation, coordination with other land-use categories, and annual inventory data incorporation.

As this is the first report to delineate C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, there are many improvements necessary. Since the accounting approach used this year operates at the regional scale for the United States, research will occur to leverage auxiliary information (i.e., remotely sensed information) to operate at finer scales in future accounting approaches. As in past submissions, deforestation is implicitly included in the report given the annual forest inventory system but not explicitly estimated. Carbon dioxide, CH_4 and N_2O emissions from forest lands with drained organic soils were not included in this Inventory.

We will apply the latest guidance in the Wetlands Supplement (IPCC 2014) by including CO₂, CH₄ and N₂O emissions from forest lands with drained organic soils in future submissions. The transparency and repeatability of accounting systems will be increased through the dissemination of open source code (e.g., R programming language) in concert with the public availability of the annual forest inventory data (USDA 2015b). Also, several FIA database processes will be institutionalized to increase efficiency and QA/QC in reporting and further improve transparency, consistency, and availability of data used in reporting. Finally, a Tier 1 approach was 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 (Woodall et al. 2015a) which will be considered in future Inventory reports.

In the current Inventory, the approach to estimating the soil C pool was refined by incorporating a national inventory of SOC (O’Neil et al. 2005) in combination with auxiliary soil, site, and climate information (Domke et al. In prep). 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. In prep). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014), are being explored but may require additional investment in field inventories before improvements can be realized with Inventory submissions.

The foundation of forest C accounting is the annual forest inventory system. 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 2015b), particularly in western states. Hawaii and U.S. Territories will be included when appropriate forest C data are available (as of July 21, 2015, Hawaii is not yet reporting any data from the annualized sampling design). Forest lands in interior Alaska (AK) are not yet included in this report as an annual inventory has never been conducted in this remote region. A pilot study of an efficient method for inventorying forest C stocks in interior AK (Woodall et al. 2015) has been conducted with results still being evaluated. Although an annual forest inventory of interior AK may be implemented in the 2016 field season, alternative methods of estimating C stock change will need to be explored as it may take over a decade to re-measure newly established plots in the 2016 field season. To that end, research is underway to incorporate all FIA plot information (both annual and periodic data) and the Landsat and MODIS time-series (along with other remotely sensed data) in a design-based, model-assisted format for estimating GHG emissions and removals as well as change detection across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid not only the interior AK 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 FIA sampling frame extends beyond the forest land use category (e.g., woodlands and urban areas) with inventory-relevant information for these lands which will likely become increasingly available in coming years.

Non-CO₂ Emissions from Forest Fires

Emissions of non-CO₂ gases from forest fires were estimated using U.S.-specific data for annual area of forest burned and potential fuel availability as well as the default IPCC (2006) emissions and combustion factors applied to the IPCC methodology. Emissions from this source in 2014 were estimated to be 7.3 MMT CO₂ Eq. of CH₄ and 4.8 MMT CO₂ Eq. of N₂O (Table 6-15, kt units available in Table 6-16). The estimates of non-CO₂ emissions from forest fires account for wildfires in the conterminous 48 states and Alaska as well as prescribed fires.

Table 6-15: Estimated Non-CO₂ Emissions from Forest Fires (MMT CO₂ Eq.) for U.S. Forests

Gas	1990	2005	2010	2011	2012	2013	2014 ^a
CH ₄	3.3	9.9	3.3	6.6	11.1	7.3	7.3
N ₂ O	2.2	6.5	2.2	4.4	7.3	4.8	4.8
Total	5.4	16.5	5.4	11.0	18.3	12.2	12.2

^aThe data for 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Table 6-16: Estimated Non-CO₂ Emissions from Forest Fires (kt) for U.S. Forests

Gas	1990	2005	2010	2011	2012	2013	2014 ^a
CH ₄	131	397	131	265	443	294	294
N ₂ O	7	22	7	15	24	16	16
CO	2,792	8,515	2,845	5,683	9,499	6,298	6,298
NO _x	78	239	80	159	266	177	177

^a The data for 2014 were incomplete when these estimates were summarized; therefore 2013, the most recent available estimate, is applied to 2014.

Methodology

Non-CO₂ emissions from forest fires—specifically for CH₄ and N₂O emissions—were calculated following IPCC (2006) methodology, which included a combination of U.S. specific data on area burned and potential fuel available for combustion along with IPCC default combustion and emission factors. The estimates were calculated according to model 2.27 of IPCC (2006, Volume 4, Chapter 2), which in general terms is:

$$\text{Emissions} = \text{Area burned} \times \text{Fuel available} \times \text{Combustion factor} \times \text{Emission factor} \times 10^{-3}$$

where area burned is based on Monitoring Trends in Burn Severity (MTBS) data summaries (MTBS 2015), fuel estimates are based on current carbon density estimates obtained from the latest FIA data for each state, and combustion 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-CO₂ emissions from forest fires calculated as described above, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainty in the model as it was 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-CO₂ Emissions from Forest Fires in Forest Land Remaining Forest Land (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate ^a			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO ₂ Emissions from Forest Fires	CH ₄	7.3	1.0	20.1	-86%	+174%
Non-CO ₂ Emissions from Forest Fires	N ₂ O	4.8	1.2	12.4	-76%	+157%

^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 2014. 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 forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the Inventory process. Further, the set of fire emissions estimates using MODIS imagery and post-fire observations developed for Alaska by Veraverbeke et al. (2015) (Table A-16) were used to compare with the estimates of CO₂ and C emissions from forest fires in Alaska (Table 6-13 and A-14). The alternate sources of data for annual areas burned and possible fuel availability were found to be similar to the data in use here. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current non-CO₂ emissions estimates are based on the calculation described above and in IPCC (2006), which is a very similar approach to the basic calculation of previous Inventory reports. However, some of the data summarized and applied to the calculation are very different for the current Inventory. The use of the MTBS data summaries is the most prominent example. Annual burned areas on managed forest lands were identified according to Ruefenacht et al. (2008) and Ogle et al. (In preparation). The other change with the current Inventory estimates is in the use of the underlying plot level carbon densities based on forest inventory plots. Although the base data are similar to past years, the current uncertainty estimates are based on an assumption that plot-to-plot variability is a greater influence on uncertainty than the uncertainty in the forest-inventory to C conversion factors (as employed for uncertainty in the past). See Annex 3.13 for additional details.

Planned Improvements

Possible future improvements within the context of this same IPCC (2006) methodology are most likely to involve greater specificity by fire or groups of fires and less reliance on wide regional values or IPCC defaults. Spatially relating potential fuel to more localized forest structure is the best example of this. An additional improvement would be combustion factors more locally appropriate for the type, location, and intensity of fire, which are currently unused information provided with the MTBS data summaries. All planned improvements depend on future availability of appropriate U.S.-specific data.

N₂O Fluxes from Forest Soils (IPCC Source Category 4A1)

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 forestland area.

N additions to soils result in direct and indirect N₂O 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 in a form other than N₂O (ammonia [NH₃] and nitrogen oxide [NO_x] volatilization, nitrogen trioxide [NO₃] leaching and runoff), and later converted into N₂O 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 N₂O emissions from forest soils in 2014 were 0.3 MMT CO₂ Eq. (1 kt), and the indirect emissions were 0.1 MMT CO₂ Eq. (0.4 kt). Total emissions for 2014 were 0.5 MMT CO₂ Eq. (2 kt) and have increased by 455 percent from 1990 to 2014. Increasing emissions over the time series is a result of greater area of N fertilized pine plantations in the southeastern United States and Douglas-fir timberland in western Washington and Oregon. Total forest soil N₂O emissions are summarized in Table 6-18.

Table 6-18: N₂O Fluxes from Soils in Forest Land Remaining Forest Land (MMT CO₂ Eq. and kt N₂O)

	1990	2005	2010	2011	2012	2013	2014
Direct N₂O Fluxes from Soils							
MMT CO ₂ Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N ₂ O	+	1	1	1	1	1	1
Indirect N₂O Fluxes from Soils							
MMT CO ₂ Eq.	0.0	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
kt N ₂ O	+	2	2	2	2	2	2

+ Does not exceed 0.05 MMT CO₂ Eq. or 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology

The IPCC Tier 1 approach is used to estimate N₂O from soils within *Forest Land Remaining 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 accounted for N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N₂O 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). Not accounting for fertilizer applied to non-pine plantations is justified because fertilization is routine for pine forests but rare for hardwoods (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 2014, 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 and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2014, 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 N₂O 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 for the portion of volatilized N that is converted to N₂O off-site. 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 N₂O off-site. The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N₂O 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 N₂O flux 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 estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only synthetic N fertilizers are captured, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils is included in Section 5.4 Agricultural Soil Management and Section 6.10 Settlements Remaining Settlements.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level²⁹ 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 2005 activity data and emission factor input variables are directly applied to the 2014 emission estimates. IPCC (2006) provided estimates for the uncertainty associated with direct and indirect N₂O 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 N₂O fluxes from soils in 2014 are estimated to be between 0.1 and 1.1 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2014 emission estimate of 0.3 MMT CO₂ Eq. Indirect N₂O emissions in 2014 are between 0.02 and 0.4 MMT CO₂ Eq., ranging from 86 percent below to 238 percent above the 2014 emission estimate of 0.1 MMT CO₂ Eq.

²⁹ Uncertainty is unknown for the fertilization rates so a conservative value of ± 50 percent is used in the analysis.

Table 6-19: Quantitative Uncertainty Estimates of N₂O Fluxes from Soils in *Forest Land Remaining Forest Land* (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Land Remaining Forest Land						
Direct N ₂ O Fluxes from Soils	N ₂ O	0.3	0.1	1.1	-59%	+211%
Indirect N ₂ O Fluxes from Soils	N ₂ O	0.1	+	0.4	-86%	+238%

+ Does not exceed 0.05 MMT CO₂ Eq.

Note: These estimates include direct and indirect N₂O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet tab containing fertilizer applied to forests and calculations for N₂O and uncertainty ranges are checked and verified.

Planned Improvements

Additional data will be compiled to update estimates of forest areas receiving N fertilizer as new reports are made available. Another improvement is to further disaggregate emissions by state for southeastern pine plantations and northwestern Douglas-fir forests to estimate soil N₂O emission. This improvement is contingent on the availability of state-level N fertilization data for forest land.

6.3 Land Converted to Forest Land (IPCC Source Category 4A2)

The C stock change estimates for *Land Converted to Forest Land* that are provided in this section include all forest land in an inventory year that had been in another land use(s) during the previous 20 years³⁰ (USDA NRCS 2009). For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Recently-converted lands are in this category for 20 years as recommended in the 2006 *IPCC Guidelines* (IPCC 2006). It is also important to note that the accounting framework used this year to develop estimates of C stock change for *Forest Land Remaining Forest Land* and intended to be used for *Land Converted to Forest Land* was not fully developed for this Inventory and therefore only estimates of C stock changes from mineral soils are included in *Land Converted to Forest Land* following Ogle et al (2003, 2006) and IPCC (2006). Carbon stock changes for the other pools (i.e., aboveground and belowground biomass, dead wood, and litter), as recommended for inclusion by IPCC (2006) are not included for the *Land Converted to Forest Land* category in this Inventory, but research is underway to include these IPCC pools in subsequent submissions of the Inventory. This was due, in part, for a need to more thoroughly quantify the length of time that land remains in a conversion category after a change in land use and also because the accounting framework was not fully developed in time to estimate C stocks and

³⁰ The 2009 USDA National Resources Inventory (NRI) land-use survey points were classified according to land-use history records starting in 1982 when the NRI survey began. Consequently the classifications from 1990 to 2001 were based on less than 20 years.

stock changes for the IPCC pools over the default 20-year conversion period in the *Land Converted to Forest Land* category.

Area of Land Converted to Forest in the United States

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 1990 to the present at an approximate rate of 1 million ha year⁻¹. 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 converted forested land in the United States were allowed to revert to forests or were actively reforested (Birdsey et al. 2006). The impacts of these land-use changes still influence C fluxes from these forest lands (land-use change legacy effects, Woodall et al. 2015b). 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. 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).

The conversion of grassland to forest land resulted in the largest source of soil C sequestration (accounting for approximately 68 percent of the sequestration in the category in 2014), though gains have decreased over the time series which is the result of less conversion into the forest land category in recent years (see Table 6-20). The net flux of C from the mineral soil stock changes in 2014 was -0.3 MMT CO₂ Eq. (-0.1 MMT C) (Table 6-20 and Table 6-21). Note that soil carbon has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. In preparation) while other land-use categories report soil carbon to a depth of 20 or 30 cm. 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).

Table 6-20: Net CO₂ Flux from Soil C Stock Changes in *Land Converted to Forest Land* by Land Use Change Category (MMT CO₂ Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Cropland Converted to Forest Land							
Mineral Soil	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land							
Mineral Soil	(0.4)	(0.5)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Other Land Converted to Forest Land							
Mineral Soil	(0.1)	(0.1)	+	+	+	+	+
Settlements Converted to Forest Land							
Mineral Soil	+	+	+	+	+	+	+
Wetlands Converted to Forest Land							
Mineral Soil	+	+	+	+	+	+	+
Total Mineral Soil Flux	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Total Soil Flux	(0.7)	(0.8)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)

+ Absolute value does not exceed 0.05 MMT CO₂ Eq.

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

Table 6-21: Net C Flux from Soil C Stock Changes in *Land Converted to Forest Land* by Land Use Change Category (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Cropland Converted to Forest Land							
Mineral Soil	+	(0.1)	+	+	+	+	+
Grassland Converted to Forest Land							
Mineral Soil	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Other Land Converted to Forest Land							
Mineral Soil	+	+	+	+	+	+	+
Settlements Converted to Forest Land							

Mineral Soil	+		+		+		+		+		+	
Wetlands Converted to Forest Land												
Mineral Soil	+		+		+		+		+		+	
Total Mineral Soil Flux	(0.2)		(0.2)		(0.1)		(0.1)		(0.1)		(0.1)	
Total Soil Flux	(0.2)		(0.2)		(0.1)		(0.1)		(0.1)		(0.1)	

+ Absolute value does not exceed 0.05 MMT C.

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

Methodology

The following section includes a description of the methodology used to estimate changes in mineral soil C stocks for *Land Converted to Forest Land*. Carbon stock changes for the other pools (i.e., aboveground and belowground biomass, dead wood, and litter), as recommended for inclusion by IPCC (2006) for each land use and land use conversion category are not included in this Inventory. This was due, in part, for a need to more thoroughly quantify the length of time that land remains in a conversion category after a change in land use and also because the accounting framework was not developed in time to estimate C stocks and stock changes for the IPCC pools in the *Land Converted to Forest Land* category over the default 20-year conversion period. Improvements are underway to include all C pool estimates in future inventories.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate 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 2010 National Resources Inventory (NRI) (USDA-NRCS 2013), and National Land Cover Dataset (NLCD) (Homer et al. 2007). See Annex 3.12 for more information about this method (Methodology for Estimating N₂O Emissions, CH₄ Emissions and Soil Organic C Stock Changes from Agricultural Soil Management).

Uncertainty and Time-Series Consistency

Uncertainty estimates for mineral soil C stock changes were developed using the same methodologies as described for the Tier 2 component of the mineral soils in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-22 for each land conversion category. Uncertainty estimates were obtained using a Monte Carlo approach. Uncertainty estimates were combined using the error propagation model in accordance with IPCC (2006). The combined uncertainty for soil C stocks in *Land Converted to Forest Land* ranged from 70 percent below to 67 percent above the 2014 stock change estimate of -0.3 MMT CO₂ Eq.

Table 6-22: Quantitative Uncertainty Estimates for Mineral Soil C Stock Changes (MMT CO₂ Eq. per yr) in 2014 Occurring Within *Land Converted to Forest Land*

Source	2014 Flux Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Flux Range ^a			
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land					
Mineral Soils Tier 2	(0.1)	(0.1)	+	-99%	94%
Grassland Converted to Forest Land					
Mineral Soils Tier 2	(0.2)	(0.5)	+	-99%	94%
Other Lands Converted to Forest Land					
Mineral Soils Tier 2	+	(0.1)	+	-99%	94%

Settlements Converted to Forest Land					
Mineral Soils Tier 2	+	+	+	-99%	94%
Wetlands Converted to Forest Land					
Mineral Soils Tier 2	+	+	+	-99%	94%
Total: Lands Converted to Forest Lands	(0.3)	(0.6)	(0.1)	-70%	67%

+ Does not exceed 0.05 MMT CO₂ Eq.

^a Range of flux estimate for 95 percent confidence interval

Note: Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of biomass, litter and dead wood C stock changes in this category. The accumulation of biomass, litter and dead wood in this category may have led to substantial changes in the biomass, litter and dead wood C stocks in some regions of the U.S. These stock changes will be included in future submissions (see Planned Improvements below).

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland*.

Recalculations Discussion

This is the first U.S. submission to include a *Land Converted to Forest Land* section containing specific soil C stock change estimates. In prior submissions (e.g., EPA 2015), the C stock changes from *Land Converted to Forest Land* were a part of the *Forest Land Remaining Forest Land* estimates. As such, no recalculations were conducted for this chapter in this year's submission. See the Recalculations section in *Forest Land Remaining Forest Land* for a detailed explanation on overall changes resulting from implementing a different accounting approach in the current Inventory report.

Planned Improvements

A different accounting framework (Woodall et al. 2015a) was used for the forest land category in this report with the specific intent of separating *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. While this new approach led to improvements (e.g., disaggregation of forest land area between the land-use categories), there are many improvements still necessary to fully incorporate all C pool estimates and all land-use categories over the entire time series. First, research, in coordination with the other land-use categories, into the length of time that forest land remains in the *Land Converted to Forest Land* category will be undertaken and a mechanism to account for emissions and removals for all IPCC pools in this conversion category will be developed. Second, soil carbon has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. In preparation) while other land-use categories (e.g., Grasslands and Croplands) report soil carbon to a depth of 20 or 30 cm. To ensure 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. In prep) to estimate soil carbon to depths of 20, 30, and 100 cm the in 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 conversion categories and Domke et al. (In preparation) will be used in the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* categories to ensure consistent accounting across all forest land. Third, only estimates of mineral soil C are included in the *Land Converted to Forest Land* category this year. This led to an incomplete Inventory since the other IPCC pools were not included. In subsequent reports, all IPCC pools will be included in the *Land Converted to Forest Land* category. This will require coordination between land-use categories to ensure incorporation of country-specific or IPCC Tier 1 estimates for all IPCC C pools to ensure complete and consistent accounting between land-use categories.

6.4 Cropland Remaining Cropland (IPCC Source Category 4B1)

Mineral and Organic Soil Carbon Stock Changes

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, with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards. Within soils, C is found in organic and inorganic forms of C, but soil organic C (SOC) is the main source and sink for atmospheric CO₂ in most soils. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on both mineral and organic soils.³¹

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 during the 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 SOC 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, and flooding, can modify both organic matter inputs and decomposition, and thereby result in a net C stock change (Parton et al. 1987; Paustian et al. 1997a; Conant et al. 2001; Ogle et al. 2005). 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 CO₂ emissions.³² 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 (and also settlements) 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 used as cropland for the previous 20 years according to the 2010 United States Department of Agriculture (USDA) National Resources Inventory (NRI) land-use survey for non-federal lands (USDA-NRCS 2013) and according to the National Land Cover Dataset for federal lands (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land used to produce food and fiber, in addition to forage that is harvested and used as feed (e.g., hay and silage), and cropland that has been enrolled in the Conservation Reserve Program (CRP) (i.e., considered reserve 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 total amount of managed area in *Cropland Remaining Cropland* (see Section 6.1 Representation of the U.S. Land Base) and the cropland area included in the Inventory analysis (0.5 to 0.7 million hectares or 0.02 percent of the total cropland areas in the United States between 1990 and 2014). Improvements are underway to include croplands in Alaska and other miscellaneous cropland areas as part of future C inventories.

³¹ Carbon dioxide emissions associated with liming are also estimated but are included in a separate section of the report.

³² Note: N₂O emissions from soils are included in the Agricultural Soil Management section.

Carbon dioxide emissions and removals³³ due to changes in mineral soil C stocks are estimated using a Tier 3 Approach 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 Methodology section for a list of crops in the Tier 2 and 3 methods) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shale soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale) regardless of crop, and for additional changes in mineral soil C stocks that are not addressed with the Tier 3 approach (i.e., change in C stocks after 2010 due to CRP enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

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 6-23 and Table 6-24). (Note: Estimates after 2010 are based on NRI data from 2010 and therefore do not fully reflect changes occurring in the latter part of the time series). In 2014, mineral soils are estimated to sequester 36.2 MMT CO₂ Eq. from the atmosphere (9.9 MMT C). This rate of C storage in mineral soils represents about a 42 percent decrease in the rate since the initial reporting year of 1990. CO₂ emissions from organic soils are 27.8 MMT CO₂ Eq. (7.6 MMT C) in 2014, which is a 0.8 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 8.4 MMT CO₂ Eq. (2.3 MMT C) in 2014.

Table 6-23: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO₂ Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(62.3)	(42.8)	(26.0)	(40.3)	(38.9)	(37.0)	(36.2)
Organic Soils	28.0	28.7	27.8	27.8	27.8	27.8	27.8
Total Net Flux	(34.3)	(14.1)	1.8	(12.5)	(11.2)	(9.3)	(8.4)

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-24: Net CO₂ Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(17.0)	(11.7)	(7.1)	(11.0)	(10.6)	(10.1)	(9.9)
Organic Soils	7.6	7.8	7.6	7.6	7.6	7.6	7.6
Total Net Flux	(9.4)	(3.8)	0.5	(3.4)	(3.0)	(2.5)	(2.3)

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The major cause of the reduction in soil C accumulation over the time series (i.e., 2014 is 75 percent less than 1990) is the decline in annual cropland enrolled in the CRP³⁴ which was initiated in 1985. For example, over 2 million hectares that had been enrolled in the CRP were returned to agricultural production during the last 5 years resulting in a loss of soil C. However, positive increases in C stocks continue on the nearly 10 million hectares of land currently enrolled in the CRP, as well as from intensification of crop production by limiting the use of bare-summer fallow in semi-arid regions, increased hay production, and adoption of conservation tillage (i.e., reduced- and no-till practices).

³³ Note that removals occur through uptake of CO₂ into crop and forage biomass that is later incorporated into soil C pools.

³⁴ 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.

The spatial variability in the 2014 annual C stock changes are displayed in Figure 6-4 and Figure 6-5 for mineral and organic soils, respectively. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the region with the largest amounts of conservation tillage, and the next highest rates of C accumulation occur in the South-central and Northwest regions of the United States. The regions with the highest rates of emissions from organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

Figure 6-4: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2014, Cropland Remaining Cropland

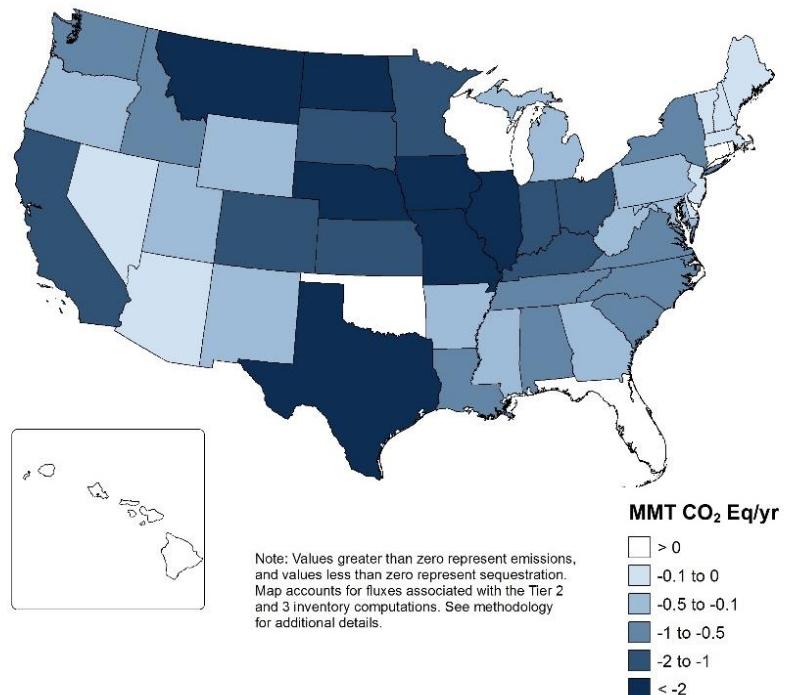
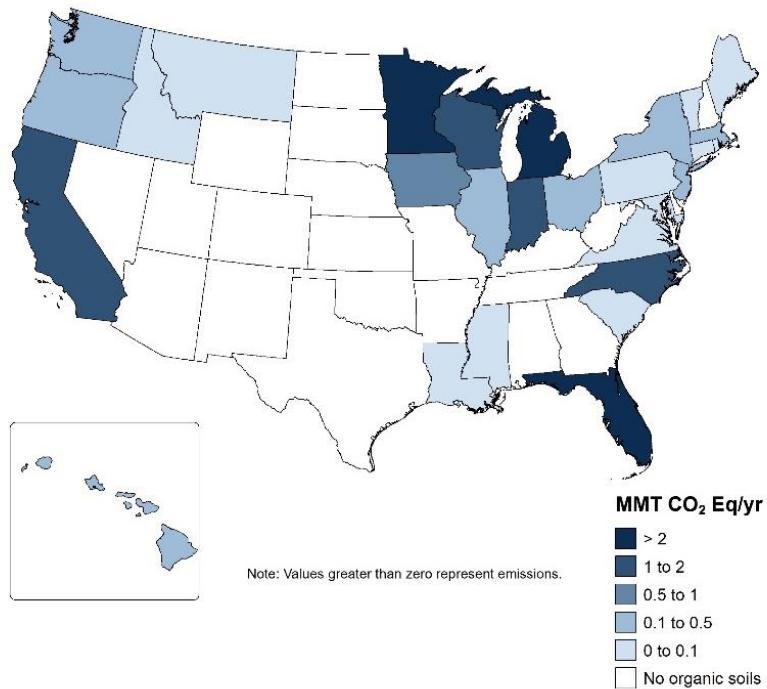


Figure 6-5: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2014, *Cropland Remaining Cropland*



Methodology

The following section includes a description of the methodology used to estimate changes in soil 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.

Soil C stock changes 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 2013). The NRI is a statistically-based sample of all non-federal land, and includes approximately 596,787 survey locations in agricultural land for the conterminous United States and Hawaii.³⁵ Each survey location is associated with an “expansion factor” that allows scaling of C stock changes from NRI survey locations to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data had 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 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2010 if the land use had 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 prior to 1979.

³⁵ NRI survey locations are classified as agricultural if under grassland or cropland management between 1990 and 2010.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. The model-based approach uses the DAYCENT biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil C stock changes and soil nitrous oxide emissions from agricultural soil management. 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 N₂O) 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, tobacco, 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 stock changes on federal croplands are estimated with the Tier 2 method. Mineral SOC 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. The Tier 2 methods is also used to estimate additional stock changes on lands enrolled in CRP after 2010, which is the last year of data in the NRI time series, using aggregated data on CRP enrollment compiled by the USDA Farm Services Agency.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.12.

Tier 3 Approach

Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical³⁶ 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. The modeling approach uses daily weather data as an input, along with information about soil physical properties. 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, residue removal, grazing, and fire). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands³⁷ (Potter et al. 1993, 2007). The model also simulates soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrients (N, P, K, S). 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 6-4 for additional information).

Box 6-4: 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 C stock changes on the majority of agricultural land on mineral soils. This approach results in a more complete and accurate accounting of soil C stock 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 and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven

³⁶ Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

³⁷ 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 2010. 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.

- 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 simplified spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 of combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at more than 300,000 individual NRI survey locations in individual fields.
 - (3) The IPCC Tier 1 and 2 methods use simplified equilibrium step changes for changes in C emissions. In contrast, the Tier 3 approach simulates a continuous time period. More specifically, the DAYCENT model (i.e., daily time-step version of the Century model) simulates soil C dynamics (and CO₂ emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil C stocks are influenced by multiple sources 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 2010 USDA NRI survey (USDA-NRCS 2013). Additional sources of activity data are used to supplement the land-use information from the NRI. The Conservation Technology Information Center (CTIC 2004) provided annual data on tillage activity at the county level for the conterminous United States between 1989 and 2004, and these data are adjusted for long-term adoption of no-till agriculture (Towery 2001). Information on fertilizer use and rates by crop type for different regions of the United States are obtained primarily from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and then became the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2011).³⁸ Additional data are compiled through other sources particularly the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (Edmonds et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used to adjust the area amended with manure (see Annex 3.12 for further details). Greater availability of managed manure N relative to 1997 is assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area. Data on the county-level N available for application are estimated for managed systems based on the total amount of N excreted in manure minus N losses during storage and transport, and include the addition of N from bedding materials. Nitrogen losses include direct N₂O emissions, volatilization of ammonia and NO_x, N runoff and leaching, and the N in poultry manure used as a feed supplement. More information on livestock manure production is available in Section 5.2 - Manure Management and Annex 3.11.

Daily weather data are another input to the model simulations, and these data are based on a 4 kilometer gridded product from the PRISM Climate Group (2015). Soil attributes are obtained from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2015). The C dynamics at each NRI point are simulated 100 times as part of the uncertainty analysis, yielding a total of over 18 million simulation runs for the analysis. Uncertainty in the C stock estimates from DAYCENT associated with parameterization and model algorithms are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007, 2010). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010. C stock changes from 2011 to 2014 are assumed to be similar to 2010 for this Inventory. Future Inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see Planned Improvements section).

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 stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference

³⁸ See <<http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/arms-data.aspx>>.

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 provided a more robust sample for estimating the reference condition. U.S.-specific C stock change factors are derived from published literature to determine the impact of management practices on SOC storage (Ogle et al. 2003, Ogle et al. 2006). The factors include changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. U.S. 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.

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-14). IPCC climate zones are then assigned to NRI point locations.

Activity data are primarily based on the historical land-use/management patterns recorded in the 2010 NRI (USDA-NRCS 2013). Each NRI point is classified by land use, soil type, climate region, and management condition. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled at these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Land-use patterns at the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Classification of cropland area by tillage practice is based on data from the Conservation Technology Information Center (CTIC 2004; Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land are obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period are based on application rates and areas amended with manure N from Edmonds et al. (2003), in addition to the managed manure production data discussed in the methodology subsection for the Tier 3 analysis.

Combining information from these data sources, SOC stocks for mineral soils are estimated 50,000 times for each year in the time series, using a Monte Carlo stochastic simulation approach and probability distribution functions for U.S.-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2002; Ogle et al. 2003; Ogle et al. 2006). The annual C stock changes from 2011 through 2014 for the Tier 2 method is assumed to be similar to 2010 because no additional activity data are available from NRI for these latter years. As with the Tier 3 method, future Inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see Planned Improvements section).

Additional Mineral C Stock Change

Annual C stock change estimates for mineral soils between 2011 and 2014 are adjusted to account for additional C stock changes associated with gains or losses in soil C after 2010 due to changes in CRP enrollment (USDA-FSA 2014). The change in enrollment relative to 2010 is based on data from USDA-FSA (2014) for 2011 through 2014. The differences in mineral soil areas are multiplied by 0.5 metric tons C per hectare per year to estimate the net effect on soil C stocks. 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 *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates included a measure of uncertainty as determined from the Monte Carlo Stochastic Simulation with 50,000 iterations. Emissions are based on the annual data for drained organic soils from 1990 to 2010 for *Cropland Remaining Cropland* areas in the 2010 NRI (USDA-NRCS 2013). The annual emissions estimated for 2010 are applied to 2011 through 2014. Future Inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (see Planned Improvements section).

Uncertainty and Time-Series Consistency

Uncertainty associated with the *Cropland Remaining Cropland* land-use category is addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table

6-25 for each subsource (mineral soil C stocks and organic soil C stocks) and the method that is used in the Inventory analysis (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), but the C stock changes from the individual 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 C stocks in *Cropland Remaining Cropland* ranged from 401 percent below to 414 percent above the 2014 stock change estimate of -8.4 MMT CO₂ Eq.

Table 6-25: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO₂ Eq. and Percent)

Source	2014 Flux Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Flux Estimate ^a (%)			
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(36.7)	(69.0)	(4.5)	-88%	+88%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(5.2)	(1.5)	-64%	+54%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	3.7	1.9	5.6	-50%	+50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	27.8	17.8	41.0	-36%	+48%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	(8.4)	(42.3)	26.5	-401%	+414%

^a Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Parentheses indicate net sequestration.

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 U.S. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may be significantly changing biomass C stocks over the Inventory times series, 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. However, 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

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 a statistical relationship has been developed to assess uncertainties in the predictive capability of the model. The comparisons included over 80 long-term experiments, representing about 908 combinations of management treatments across all of the sites (see Ogle et al. 2007 and Annex 3.12 for more information). Quality control identified problems with simulation of hydric soils in the equilibrium and base histories, which proceed the simulation of the NRI histories from 1979 to 2010. Hydric soils were draining more quickly than expected in the simulations, and resulted in low values for the carbon stocks at the beginning of the history in 1979. Corrective actions were taken by adjusting the parameters to reduce the drainage rate on hydric soils during the equilibrium and simulate slower decomposition rates with a high water table.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal croplands; and 3) improving the simulation of hydric soil. As a result of these improvements, the change in SOC stocks declined by an average of 16.5 MMT CO₂ Eq., which is a 48 percent change in the reported soil C stock changes compared to the previous Inventory. The largest driver of this change is associated with corrective actions taken to more accurately represent the hydric soil condition.

Planned Improvements

Two major planned improvements are underway. The first is to update the time series of land use and management data from the USDA NRI so that it is extended from 2010 through 2012 for both the Tier 2 and 3 methods (USDA-NRCS 2015). Fertilization and tillage activity data will also be updated as part of this improvement. The remote-sensing based data on the Enhanced Vegetation Index will be extended through 2012 in order to use the EVI data to drive crop production in DAYCENT. Overall, this improvement will extend the time series of activity data for the Tier 2 and 3 analyses through 2012.

The second major planned improvement is to analyze C stock changes in Alaska for cropland and managed grassland, 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 C stock changes, but will be further refined over time to incorporate more of the management data.

An improvement is also underway to simulate crop residue burning in the DAYCENT based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (Section 5.5). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning. Other improvements are underway to refine the production part of the DAYCENT biogeochemical model. For example, senescence events following grain filling in crops, such as wheat, have been refined based on recent model algorithm development, and will be incorporated into next year's Inventory.

All of these improvements are expected to be completed for the 1990 through 2015 Inventory. However, the time line may be extended if there are insufficient resources to fund all or part of these planned improvements.

CO₂ Emissions from Liming

IPCC (2006) recommends reporting CO₂ emissions from lime additions (in the form of crushed limestone (CaCO₃) and dolomite (CaMg(CO₃)₂) to soils. Limestone and dolomite are added 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 and ultimate magnitude 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 liming of soils have fluctuated over the past 24 years, ranging from 3.7 MMT CO₂ Eq. to 6.0 MMT CO₂ Eq. In 2014, liming of soils in the United States resulted in emissions of 4.1 MMT CO₂ Eq. (1.1 MMT C), representing an 11 percent decrease in emissions since 1990 (see Table 6-26 and Table 6-27). The trend is driven by the amount of limestone and dolomite applied to soils over the time period.

Table 6-26: Emissions from Liming (MMT CO₂ Eq.)

Source	1990	2005	2010	2011	2012	2013	2014
Limestone	4.1	3.9	4.3	3.4	4.5	3.6	3.8
Dolomite	0.6	0.4	0.5	0.4	1.5	0.3	0.3
Total^a	4.7	4.3	4.8	3.9	6.0	3.9	4.1

^a Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining 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.

Note: Totals may not sum due to independent rounding.

Table 6-27: Emissions from Liming (MMT C)

Source	1990	2005	2010	2011	2012	2013	2014
Limestone	1.1	1.1	1.2	0.9	1.2	1.0	1.0
Dolomite	0.2	0.1	0.1	0.1	0.4	0.1	0.1
Total^a	1.3	1.2	1.3	1.1	1.6	1.1	1.1

^a Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, and Settlements Remaining 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.

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 applied (see Table 6-28) were multiplied by CO₂ emission factors from West and McBride (2005). These 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).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Industry Surveys* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014 and 2015; USGS 2008 through 2015). 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 6-5: 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 rivers 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 2014 U.S. emission estimate from liming of soils is 4.1 MMT CO_2 Eq. using the U.S.-specific factors. In contrast, emissions would be estimated at 8.4 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 manufacturer 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 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 2013 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 2014 data, 2013 fractions were applied to a 2014 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2015* (USGS 2015).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1994 and by the USGS from 1995 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.

Emissions from limestone and dolomite are estimated at the state level and summed to obtain the national estimate. The state-level estimates are not reported here, but are available upon request. Also, it is important to note that all emissions from liming are reported in *Cropland Remaining Cropland* because it is not possible to subdivide the data to each land-use category (i.e., *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Settlements Remaining Settlements*, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*).

Table 6-28: Applied Minerals (MMT)

Mineral	1990	2005	2010	2011	2012	2013	2014
Limestone ^a	19.0	18.1	20.0	15.9	20.8	16.6	17.5
Dolomite ^a	2.4	1.9	1.9	1.9	6.3	1.4	1.5

^a Data represent amounts applied to *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, *Settlements Remaining 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

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 smoothed

triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty. More information on the uncertainty estimates for CO₂ Emissions from Liming is contained within the Uncertainty Annex 7.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO₂ emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-29. CO₂ emissions from Liming in 2014 were estimated to be between -0.5 and 7.8 MMT CO₂ Eq. at the 95 percent confidence level. This confidence interval represents a range of 111 percent below to 88 percent above the 2014 emission estimate of 4.1 MMT CO₂ Eq.

Table 6-29: Approach 2 Quantitative Uncertainty Estimates for CO₂ Emissions from Liming (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Liming ^b	CO ₂	4.1	(0.5)	7.8	-111%	+88%

^aRange of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

^bIncludes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land and Land Converted to Forest Land*, as it is not possible to subdivide the data by land-use category.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, and the quality control effort focused on the Tier 1 procedures for this Inventory. Quality control procedures did uncover a transcription error in the spreadsheets that was corrected.

Recalculations Discussion

Adjustments were made in the current Inventory to improve the results. First, limestone and dolomite application data for 2013 were approximated in the previous Inventory using a ratio of total crushed stone for 2013 relative to 2012 (similar to 2014 in the current Inventory). The estimates for 2013 were updated with the recently published data from USGS (2015). Second, quality control measures uncovered a transcription error in the 2012 activity data that increased the emission estimate by 0.2 MMT CO₂ Eq. related to the previous Inventory. With these revisions in the activity data, the emissions increased by 3.5 percent in 2012 and decreased by 34 percent in 2013 relative to the previous Inventory.

CO₂ Emissions from Urea Fertilization

The use of urea (CO(NH₂)₂) as a fertilizer leads to CO₂ emissions through the release of CO₂ that was fixed during the industrial production process. In the presence of water and urease enzymes, urea is converted into ammonium (NH₄⁺), hydroxyl ion (OH), and bicarbonate (HCO₃⁻). The bicarbonate then evolves into CO₂ and water. Emissions from urea fertilization in the United States totaled 4.5 MMT CO₂ Eq. (1.2 MMT C) in 2014 (Table 6-30 and Table 6-31). Due to an increase in application of urea fertilizers between 1990 and 2014, CO₂ emissions have increased by 87 percent from this management activity.

Table 6-30: CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq.)

Source	1990	2005	2010	2011	2012	2013	2014
Urea Fertilization ^a	2.4	3.5	3.8	4.1	4.2	4.3	4.5

^a Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining 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.

Table 6-31: CO₂ Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2010	2011	2012	2013	2014
Urea Fertilization ^a	0.7	1.0	1.0	1.1	1.2	1.2	1.2

^a Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining 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.

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 all CO₂ fixed during the industrial production process of urea are released after application. The annual amounts of urea applied to croplands (see Table 6-32) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2014). 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. Because fertilizer sales data are reported in fertilizer years (July previous year through June current year), 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. For example, for the 2000 fertilizer year, 35 percent of the fertilizer was applied in July through December 1999, and 65 percent was applied in January through June 2000.

Fertilizer sales data for the 2013 and 2014 fertilizer years (i.e., July 2012 through June 2013 and July 2013 through June 2014) were not available for this Inventory. Therefore, urea application in the 2013 and 2014 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2008 through 2012) at the state level. 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 CO₂ 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 data using the method described above.

Emissions are estimated at the state level and summed to obtain the national estimate. The state-level estimates are not reported here, but are available upon request. Also, it is important to note that all emissions from urea fertilization are reported in *Cropland Remaining Cropland* because it is not currently possible to apportion the emissions to each land-use category (i.e., *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements, Forest Land Remaining Forest Land and Land Converted to Forest Land*), however, the majority of urea fertilization is likely to have occurred on *Cropland Remaining Cropland*.

Table 6-32: Applied Urea (MMT)

	1990	2005	2010	2011	2012	2013	2014
Urea Fertilizer ^a	3.3	4.8	5.2	5.6	5.8	5.9	6.2

^aThese 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, 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

Uncertainty estimates are presented in Table 6-33 for *Urea Fertilization*. An Approach 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C in CO(NH₂)₂ applied to soils is ultimately emitted into the environment as CO₂. This factor does not incorporate the possibility that some of the C may be retained in the soil, and therefore the uncertainty range was set from 0 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, each urea consumption data point has an associated uncertainty. Carbon dioxide emissions from urea fertilization of agricultural soils in 2014 were estimated to be between 2.6 and 4.5 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of 42 percent below to 0 percent above the 2014 emission estimate of 4.5 MMT CO₂ Eq.

Table 6-33: Quantitative Uncertainty Estimates for CO₂ Emissions from Urea Fertilization (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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 Fertilization	CO ₂	4.5	2.6	4.5	-42%	0%

^aRange 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. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals, but the amount is likely very small. For example, research on aircraft deicing practices is consistent with this assumption based on a 1992 survey that found a known annual usage of approximately 2,000 tons of urea for deicing; this would constitute 0.06 percent of the 1992 consumption of urea (EPA 2000). Similarly, surveys conducted from 2002 to 2005 indicate that total urea use for deicing at U.S. airports is estimated to be 3,740 metric tons per year, or less than 0.07 percent of the fertilizer total for 2007 (Idle 2009). In addition, there is uncertainty surrounding the underlying assumptions behind the calculation that converts fertilizer years to calendar years. These uncertainties are negligible over multiple years, however, because an over- or under-estimated value in one calendar year is addressed with corresponding increase or decrease in the value for the subsequent year.

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented. For this year, the Tier 1 analysis was performed and an error was found in a formula reference to an incorrect cell in the spreadsheets.

Recalculations Discussion

In the current Inventory, the 2013 emission estimate was updated to reflect a correction to the calculations made in the previous Inventory report. Quality control checks uncovered an incorrect spreadsheet cell reference influencing

the state-level emission calculations. The 2013 emission estimate increased by 8.3 percent, relative to the previous report, due to this correction.

Planned Improvements

No improvements are planned for this source.

6.5 Land Converted to Cropland (IPCC Source 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 2013), 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 forestland 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 in the IPCC guidelines (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) or climate zones (e.g., boreal climates). Consequently there is a discrepancy between the total amount of managed area in *Land Converted to Cropland* (see Section 6.1 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 crops in future C inventories.

Land use change can lead to large losses of 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 according to a recent assessment (Tubiello et al. 2015).

The 2006 IPCC Guidelines recommend reporting changes in biomass, dead organic matter and soil organic carbon (SOC)³⁹ stocks with land use change. All soil C stock changes are estimated and reported for *Land Converted to Cropland*, but there is limited reporting of other pools in this Inventory. Loss of aboveground biomass C from *Forest Converted to Cropland* is reported but losses from belowground biomass, dead wood and litter pools with forest conversion are not included in this Inventory.⁴⁰ In addition, biomass C stock changes are not estimated for other land use conversions (other than Forest Land) to Cropland.⁴¹

Loss of aboveground woody biomass C from *Forest Converted to Cropland* is the largest contributor to C loss throughout the time series, accounting for approximately 64 percent of the total emissions (Table 6-34 and Table 6-35). *Grassland Converted to Cropland* is the largest source of emissions associated with soil C pools across the time series (accounting for approximately 91 percent of the average loss of soil C), largely because the area of *Grassland Converted to Cropland* is significantly higher than for other land use conversions to cropland, though losses declined over the time series. The net change in total C stocks for 2014 led to CO₂ emissions to the atmosphere of 22.1 MMT CO₂ Eq. (6.0 MMT C), including 11.5 MMT CO₂ Eq. (3.1 MMT C) from biomass C losses, 6.3 MMT CO₂ Eq. (1.7 MMT C) from mineral soils and 4.3 MMT CO₂ Eq. (1.2 MMT C) from drainage and cultivation of organic soils. Emissions in 2014 are 66 percent lower than the emissions in the initial reporting year of 1990, largely due to less conversion of *Forest Land to Cropland*.

³⁹ CO₂ emissions associated with liming and urea fertilization are also estimated but included in Section 6.4 *Cropland Remaining Cropland* as it was not possible to separate additions of lime and urea by land use.

⁴⁰ A planned improvement is to estimate the losses of carbon from belowground biomass, dead wood and litter with *Forest Converted to Cropland*.

⁴¹ Changes in biomass C stocks are not currently reported for other land use conversions (other than forest land) 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 (i.e., other than forest land) to cropland based on the Tier 1 method in IPCC (2006).

Table 6-34: Net CO₂ Flux from Soil C Stock Changes in Land Converted to Cropland by Land Use Change Category (MMT CO₂ Eq.)

	1990	2005	2010	2011	2012	2013	2014
Grassland Converted to Cropland							
Mineral Soils	14.2	9.1	7.9	5.8	5.8	5.9	5.9
Organic Soils	3.2	4.2	3.8	3.8	3.8	3.8	3.8
Forest Converted to Cropland							
Biomass	46.9	17.9	11.0	11.0	11.5	11.5	11.5
Mineral Soils	0.2	0.1	+	+	+	+	+
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted Cropland							
Mineral Soils	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Organic Soils	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted Cropland							
Mineral Soils	0.1	+	0.1	0.1	0.1	0.1	0.1
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Wetlands Converted Cropland							
Mineral Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.6	0.5	0.4	0.4	0.4	0.4	0.4
Total Biomass Flux	46.9	17.9	11.0	11.0	11.5	11.5	11.5
Total Mineral Soil Flux	14.7	9.5	8.4	6.3	6.3	6.3	6.3
Total Organic Soil Flux	4.0	4.8	4.3	4.3	4.3	4.3	4.3
Total Net Flux	65.7	32.2	23.7	21.6	22.0	22.1	22.1

+ Does not exceed 0.05 MMT CO₂ Eq.

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding.

Table 6-35: Net CO₂ Flux from Soil C Stock Changes in Land Converted to Cropland (MMT C)

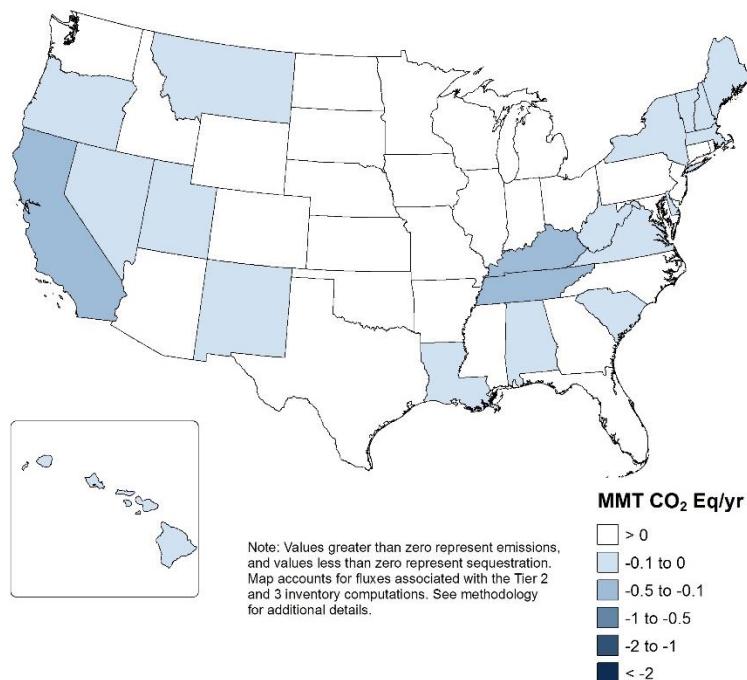
	1990	2005	2010	2011	2012	2013	2014
Grassland Converted to Cropland							
Mineral Soils	3.9	2.5	2.2	1.6	1.6	1.6	1.6
Organic Soils	0.9	1.1	1.0	1.0	1.0	1.0	1.0
Forest Converted to Cropland							
Biomass	12.8	4.9	3.0	3.0	3.1	3.1	3.1
Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted Cropland							
Mineral Soils	+	+	+	0.1	0.1	0.1	0.1
Organic Soils	+	0.0	0.0	0.0	0.0	0.0	0.0
Settlements Converted Cropland							
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted Cropland							
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Total Biomass Flux	12.8	4.9	3.0	3.0	3.1	3.1	3.1
Total Mineral Soil Flux	4.0	2.6	2.3	1.7	1.7	1.7	1.7
Total Organic Soil Flux	1.1	1.3	1.2	1.2	1.2	1.2	1.2
Total Net Flux	17.9	8.8	6.5	5.9	6.0	6.0	6.0

+ Does not exceed 0.05 MMT C

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding.

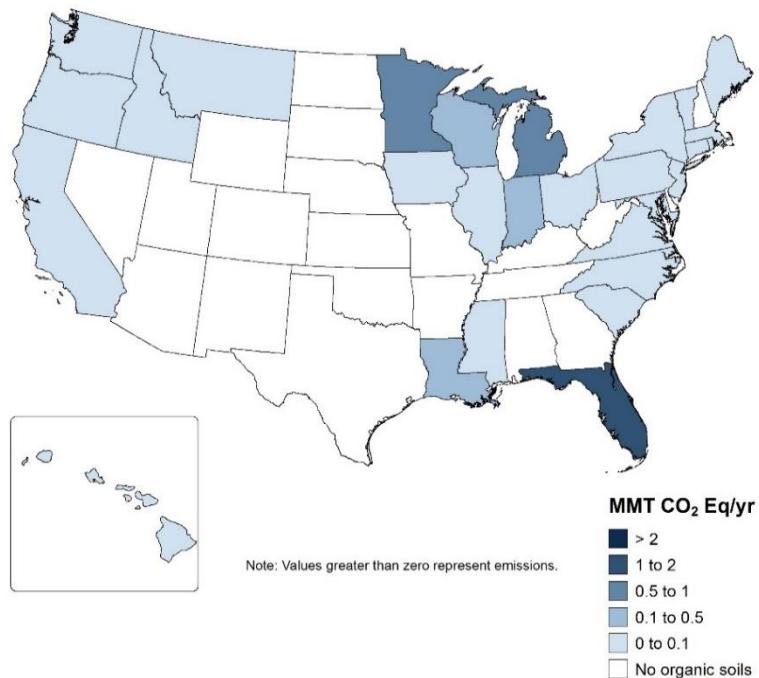
The spatial variability in the 2014 annual C stock changes⁴² for mineral soils is displayed in Figure 6-6 and for organic soils in Figure 6-7. In most states, soil C stocks declined for *Land Converted to Cropland*. This is because conversion of grassland and forestland to cropland led to enhanced decomposition of soil organic matter and a net loss of C from the soil pool. There were some exceptions to this generality, with gains in soil C in regions where the cropland is irrigated or land is converted from a grassland into hay production. These types of conversions generally lead to more inputs of fertilizer and/or water, which enhances production and carbon input to the soil. The regions with the highest rates of emissions from organic soils coincide with the largest concentrations of organic soils used for agricultural production, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast.

Figure 6-6: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2014, *Land Converted to Cropland*



⁴² A planned improvement is to include biomass C stock changes in the figures; currently the maps only include the spatial patterns associated with soil C stock changes.

Figure 6-7: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2014, Land Converted to Cropland



Methodology

The following section includes a description of the methodology used to estimate changes in C stocks for *Land Converted to Cropland*, including: (1) aboveground biomass from conversion of forest land to cropland; (2) agricultural land-use and management activities on mineral soils; and (3) agricultural land-use and management activities on organic soils. Belowground live biomass and dead organic matter C stock changes are not estimated in the current Inventory for *Land Converted to Cropland*. Further elaboration on the methodologies and data used to estimate stock changes for mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Biomass Carbon Stock Changes

A Tier 2 method is applied to estimate aboveground biomass C stock changes⁴³ for *Forest Land Converted to Cropland*. For this method, land is stratified by region, forest type, and site productivity and then assigned reference C density estimates for aboveground biomass for the cropland (assumed to be zero since no reference aboveground biomass C density estimates exist) and forest land use. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Reference C density estimates for aboveground biomass for the forest land use have been estimated from data in the Forest Inventory and Analysis (FIA) program within the USDA Forest Service (USDA Forest Service 2015). If FIA plots include data on individual trees, aboveground C density estimates are based on Woodall et al. (2011), which is also known as the component ratio method, and is a function of tree volume, species, diameter, and, in some regions, height and site quality. See Annex 3.13 for more information about reference C density estimates for forest land.

⁴³ A planned improvement is to estimate the losses of C from belowground biomass, dead wood and litter with *Forest Converted to Cropland*.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Land Converted to Cropland* according to land-use histories recorded in the 2010 USDA NRI survey for non-federal lands (USDA-NRCS 2013). 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 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Land Converted to Cropland* in a given year between 1990 and 2010 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 prior to 1979. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (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 for mineral soils on the majority of land that is used to produce annual crops in the United States. These crops include alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat. Soil C stock changes on the remaining soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables, tobacco, 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.⁴⁴

Tier 3 Approach. For the Tier 3 method, mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical⁴⁵ 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 (USDA-NRCS 2013). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but C stock changes from 2010 to 2014 are assumed to be similar to 2010. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (See Planned Improvements section in *Cropland Remaining Cropland*). See the *Cropland Remaining Cropland* section for additional discussion of the Tier 3 methodology for mineral soils.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 Approach for mineral soils in the *Cropland Remaining Cropland* section.

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 U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

The uncertainty analysis for aboveground biomass C losses with *Forest Converted to Cropland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land*

⁴⁴ 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 2013).

⁴⁵ Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006). For additional details see the Uncertainty Analysis in Annex 3.13. Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described for *Cropland Remaining Cropland*. 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.

Uncertainty estimates are presented in Table 6-36 for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) 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 total C stocks in *Land Converted to Cropland* ranged from 54 percent below to 52 percent above the 2014 stock change estimate of 22.1 MMT CO₂ Eq.

Table 6-36: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (MMT CO₂ Eq. and Percent)

Source	2014 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	9.7	(2.2)	20.3	-123%	110%
Mineral Soil C Stocks: Tier 3	4.5	(5.3)	14.4	-218%	218%
Mineral Soil C Stocks: Tier 2	1.3	(0.1)	2.2	-108%	69%
Organic Soil C Stocks: Tier 2	3.8	10.2	+	-168%	99%
Forests Converted to Cropland	11.5	9.2	13.9	-21%	21%
Biomass C Stocks	11.5	10.0	12.9	-13%	13%
Mineral Soil C Stocks: Tier 2	+	+	0.1	-111%	71%
Organic Soil C Stocks: Tier 2	+	0.1	0.0	-154%	100%
Other Lands Converted to Cropland	0.2	(+)	0.3	-112%	83%
Mineral Soil C Stocks: Tier 2	0.2	(+)	0.3	-112%	72%
Organic Soil C Stocks: Tier 2	0.0	0.0	0.1	0%	0%
Settlements Converted to Cropland	0.1	+	0.5	-71%	255%
Mineral Soil C Stocks: Tier 2	0.1	(+)	0.1	-112%	72%
Organic Soil C Stocks: Tier 2	0.1	0.1	0.4	-91%	454%
Wetlands Converted to Croplands	0.6	0.3	4.5	-53%	694%
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-75%	50%
Organic Soil C Stocks: Tier 2	0.4	0.7	4.3	-65%	908%
Total: Land Converted to Cropland	22.1	10.1	33.5	-54%	52%
Biomass C Stocks	11.5	10.0	12.9	-13%	13%
Mineral Soil C Stocks: Tier 3	4.5	(5.3)	14.4	-218%	218%
Mineral Soil C Stocks: Tier 2	1.7	0.3	2.7	-83%	53%
Organic Soil C Stocks: Tier 2	4.3	(2.1)	9.8	-148%	126%

+ Absolute value 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.

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

Uncertainty is also associated with lack of reporting of agricultural biomass and litter 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 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 significant 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 also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. However, this trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal croplands; 3) improving the simulation of hydric soils in DAYCENT, and 4) incorporating the aboveground biomass C stock losses with *Forest Land Converted to Cropland*. As a result of these improvements to the Inventory, *Land Converted to Cropland* have a larger reported loss of C, estimated at 21.0 MMT CO₂ Eq. over the time series. This represents a 100 percent increase in the losses of carbon with *Land Converted to Cropland* compared to the previous Inventory, and is largely driven by reporting aboveground biomass C loss from *Forest Converted to Croplands* in this category instead of *Forest Land Remaining Forest Land* where it was included in the previous Inventory submissions.

Planned Improvements

Soil C stock changes with land use conversion from forest land to cropland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland. This planned improvement may not be fully implemented for another year, depending on resource availability.

The impact of *Forest Land Converted to Cropland* on belowground biomass and dead organic matter pools are not estimated in the current Inventory, and so another planned improvement is to estimate changes in C stocks for these pools in the next Inventory. In addition, biomass C stock changes will be estimated for *Grassland Converted to Cropland*, as well as other land use conversions to cropland to the extent that data are available. Additional planned improvements are discussed in the *Cropland Remaining Cropland* section.

6.6 Grassland Remaining Grassland (IPCC Source Category 4C1)

Grassland Remaining Grassland includes all grassland in an Inventory year that had been classified as grassland for the previous 20 years (USDA-NRCS 2013). 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. This Inventory includes all privately-owned and federal 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 Section 6.1 Representation of the U.S. Land Base) and the grassland area included in the Inventory analysis (IPCC Source Category 4C1—Section 6.6).

Background on agricultural carbon (C) stock changes is provided in Section 6.4, *Cropland Remaining Cropland*, and will only be summarized here. Soils are the largest pool of C in agricultural land, and also have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively small and 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* (IPCC 2006) recommend reporting changes in soil organic C (SOC) stocks

due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.⁴⁶

In *Grassland Remaining Grassland*, there has been considerable variation in soil C stocks between 1990 and 2014. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes remain small on a per hectare rate across the time series even in the years with a larger total change in stocks. Land use and management generally increased soil C in mineral soils for *Grassland Remaining Grassland* between 1990 and 2010, after which the trend is reversed to a small decline in soil C. In contrast, organic soils lose a relatively constant amount of C annually from 1990 through 2014. In 2014, soil C stocks decreased by 3.8 MMT CO₂ Eq. (1.0 MMT C), with an uptake of 0.6 MMT CO₂ Eq. (0.2 MMT C) in mineral soils but a loss of 4.3 MMT CO₂ Eq. (1.2 MMT C) from organic soils (Table 6-37 and Table 6-38). The overall trend represents a 129 percent increase in the flux relative to the flux in the initial reporting year of 1990.

Table 6-37: Net CO₂ Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT CO₂ Eq.)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(19.0)	(7.7)	(11.7)	(1.2)	(0.8)	(0.6)	(0.6)
Organic Soils	6.1	4.5	4.4	4.4	4.3	4.3	4.3
Total Net Flux	(12.9)	(3.3)	(7.3)	3.1	3.6	3.8	3.8

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-38: Net CO₂ Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (MMT C)

Soil Type	1990	2005	2010	2011	2012	2013	2014
Mineral Soils	(5.2)	(2.1)	(3.2)	(0.3)	(0.2)	(0.2)	(0.2)
Organic Soils	1.7	1.2	1.2	1.2	1.2	1.2	1.2
Total Net Flux	(3.5)	(0.9)	(2.0)	0.8	1.0	1.0	1.0

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The spatial variability in the 2014 annual CO₂ flux associate with mineral soils is displayed in Figure 6-8 and organic soils in Figure 6-9. Although relatively small on a per-hectare basis, grassland soils gained C in several regions during 2014, including most of the Eastern United States and Pacific Coastal Region. 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 the Pacific Coast.

⁴⁶ CO₂ emissions associated with liming and urea fertilization are also estimated but included in Section 6.4 *Cropland Remaining Cropland*.

Figure 6-8: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2014, Grassland Remaining Grassland

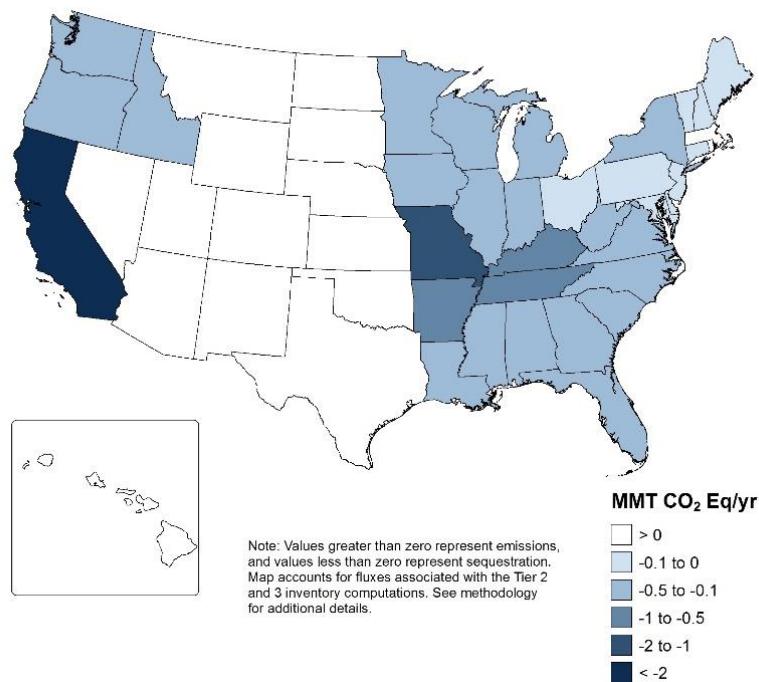
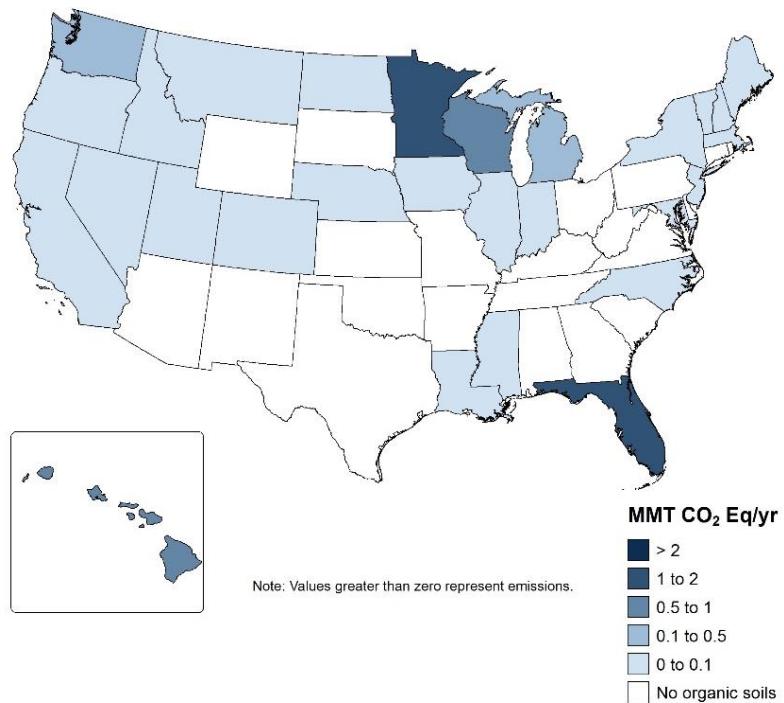


Figure 6-9: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2014, Grassland Remaining Grassland



Methodology

The following section includes a brief description of the methodology used to estimate changes in soil 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 C stock changes are estimated for *Grassland Remaining Grassland* on non-federal lands according to land use histories recorded in the 2010 USDA NRI survey (USDA-NRCS 2013). 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 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2010 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 prior to 1979. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (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 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) and additional stock changes associated with sewage sludge amendments.

Tier 3 Approach

Mineral SOC stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DAYCENT biogeochemical⁴⁷ 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 2010 USDA NRI survey (USDA-NRCS 2013). Frequency and rates of manure application to grassland during 1997 are estimated from data compiled by the USDA Natural Resources Conservation Service (NRCS) (Edmonds, et al. 2003), and then adjusted using county-level estimates of manure available for application in other years. Specifically, county-scale ratios of manure available for application to soils in other years relative to 1997 are used to adjust the area amended with manure (see *Cropland Remaining Cropland* section for further details). Greater availability of managed manure nitrogen (N) relative to 1997 is, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 is assumed to reduce the amended area.

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 (see Annex 3.11), and the remainder is deposited on federal lands (i.e., the amount that is not included in DAYCENT simulations is assumed to be applied on federal grasslands). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but C stock changes from 2011 to 2014 are assumed to be similar to 2010 because activity data are not yet available for these years. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated. See the *Cropland Remaining Cropland* section for additional discussion of the Tier 3 methodology for mineral soils.

⁴⁷ Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

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 land use and management data that are used in the Inventory for federal grasslands. The NRI (USDA-NRCS 2013) 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. These data are based on the National Land Cover Database (NLCD) (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 has compiled information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil 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.

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 2014 to account for additional C stock changes associated with sewage sludge amendments. Estimates of the amounts of sewage sludge N applied to agricultural land are derived from national data on sewage sludge generation, disposition, and N content. Although sewage sludge can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in *Grassland Remaining Grassland*. Cropland is not likely to be amended with sewage sludge due to the high metal content and other pollutants in human waste. Total sewage sludge 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. N application rates from Kellogg et al. (2000) are used to determine the amount of area receiving sludge amendments. The soil C storage rate is estimated at 0.38 metric tons C per hectare per year for sewage sludge 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 provided in IPCC (2006), which utilizes U.S.-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.

Uncertainty and Time-Series Consistency

Uncertainty analysis for mineral soil 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. 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.

Uncertainty estimates are presented in Table 6-39 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) 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 C stocks in *Grassland Remaining Grassland* ranges from -1,006 percent below to 1,013 percent above the 2014 stock change estimate of 3.8 MMT CO₂ Eq. The large relative uncertainty is due to the almost zero level of change in soil C for 2014 even though the absolute amount of uncertainty is comparable to other land-use categories in this Inventory.

Table 6-39: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within Grassland Remaining Grassland (MMT CO₂ Eq. and Percent)

Source	2014 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
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 3 Methodology	1.1	(35.8)	38.0	-3,401%	+3,401%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.3)	(8.8)	9.3	-3,307%	+3,680%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.4)	(2.1)	(0.7)	-50%	+50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	4.3	2.2	7.2	-49%	+66%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	3.8	(34.2)	42.0	-1,006%	+1,013%

^a Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

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

Uncertainty is also associated with a lack of reporting on biomass and litter C stock changes and non-CO₂ greenhouse gas emissions from grassland fires. Biomass C stock changes may be significant for managed grasslands with woody encroachment despite not having attained enough tree cover to be considered forest lands. This Inventory does not currently include the non-CO₂ greenhouse gas emissions that occur with biomass burning. Grassland burning is not as common in the United States as in other regions of the world, but fires do occur through both natural ignition sources and prescribed burning. Changes in dead organic matter C stocks are assumed to be negligible in grasslands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements, including 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal grasslands in the Tier 2 analysis; and 3) improving the simulation of hydric soils in DAYCENT. As a result of these improvements to the Inventory, SOC stocks increased on average across the time series, equivalent to an uptake of 4.9 MMT CO₂ eq., which is a 20 percent increase in the reported soil C stock changes 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 for the 1990 through 2015 Inventory. Another key planned improvement is to estimate biomass C stock changes for grasslands and non-CO₂ greenhouse gas emissions from burning of grasslands. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

6.7 Land Converted to Grassland (IPCC Source 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 years⁴⁸ (USDA-NRCS 2013). 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 Section 6.1 Representation of the U.S. Land Base) and the grassland area included in the inventory analysis (IPCC Source Category 4C2—Section 6.7).

Land-use change can lead to large losses of 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 according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommend reporting changes in biomass, dead organic matter, and soil organic C (SOC) stocks due to land use change.⁴⁹ All soil C stock changes are estimated and reported for *Land Converted to Grassland*, but there is limited reporting of other pools in this Inventory. Loss of aboveground biomass C from *Forest Converted to Grassland* is reported, but loss of C from belowground biomass, dead wood and litter pools with forest conversion are not included in this Inventory.⁵⁰ In addition, biomass C stock changes are not estimated for other land use conversions (other than forest land) to grassland.⁵¹

Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks between 1990 and 2014 (see Table 6-40 and Table 6-41). The average soil C stock change for mineral soils between 1990 and 2014 sequestered 10.6 MMT CO₂ Eq. from the atmosphere (2.9 MMT C). In contrast, over the same period, drainage of organic soils for grassland management led to CO₂ emissions to the atmosphere of 1.5 MMT CO₂ Eq. (0.4 MMT C). In addition, aboveground woody biomass C losses from *Forest Land Converted to Grasslands* led to CO₂ emissions to the atmosphere of 49.5 MMT CO₂ Eq. (13.5 MMT C) in 2014. The total net C stock change in 2014 for *Land Converted to Grassland* is estimated as a loss of 40.4 MMT CO₂ Eq. (11.0 MMT C), which is a 3 percent increase in emissions compared to the emissions in the initial reporting year of 1990.

Table 6-40: Net CO₂ Flux from Soil and Biomass C Stock Changes for *Land Converted to Grassland* (MMT CO₂ Eq.)

	1990	2005	2010	2011	2012	2013	2014
Cropland Converted to Grassland							
Mineral Soils	(6.9)	(9.7)	(9.1)	(8.6)	(8.6)	(8.6)	(8.6)

⁴⁸ 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 prior to 1979.

⁴⁹ CO₂ emissions associated with liming and urea fertilization are also estimated but included in Section 6.4 *Cropland Remaining Cropland*.

⁵⁰ A planned improvement is to estimate the losses of carbon from belowground biomass, dead wood and litter with *Forest Converted to Grassland*.

⁵¹ 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).

Organic Soils	0.5	1.0	1.1	1.2	1.2	1.2	1.2
Forest Converted to Grassland							
Biomass	47.0	54.3	49.0	49.0	49.5	49.5	49.5
Mineral Soils	(0.5)	(1.0)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted Grassland							
Mineral Soils	(0.6)	(1.1)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Organic Soils	+	0.0	+	+	+	+	+
Settlements Converted Grassland							
Mineral Soils	(0.1)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted Grassland							
Mineral Soils	(0.5)	(0.6)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	0.1	0.2	0.3	0.3	0.3	0.3	0.3
Total Biomass Flux	47.0	54.3	49.0	49.0	49.5	49.5	49.5
Total Mineral Soil Flux	(8.6)	(12.5)	(11.2)	(10.6)	(10.6)	(10.6)	(10.6)
Total Organic Soil Flux	0.7	1.2	1.5	1.5	1.5	1.5	1.5
Total Net Flux	39.1	43.1	39.3	39.9	40.4	40.4	40.4

+ Does not exceed 0.05 MMT CO₂ Eq.

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-41: Net CO₂ Flux from Soil and Biomass C Stock Changes for Land Converted to Grassland (MMT C)

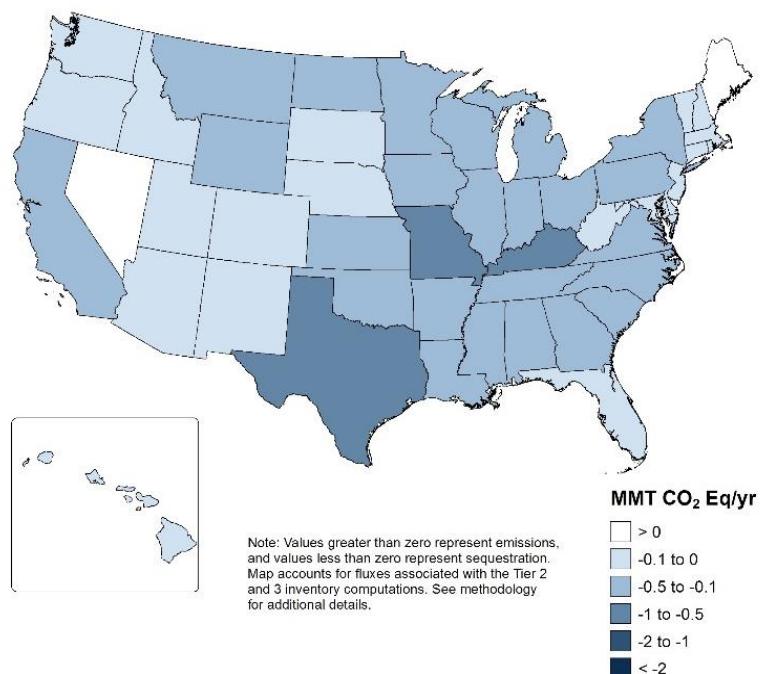
	1990	2005	2010	2011	2012	2013	2014
Cropland Converted to Grassland							
Mineral Soils	(1.9)	(2.6)	(2.5)	(2.3)	(2.3)	(2.3)	(2.3)
Organic Soils	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Forest Converted to Grassland							
Biomass	12.8	14.8	13.4	13.4	13.5	13.5	13.5
Mineral Soils	(0.1)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted Grassland							
Mineral Soils	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	0.0	+	+	+	+	+
Settlements Converted Grassland							
Mineral Soils	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted Grassland							
Mineral Soils	(0.1)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Biomass Flux	12.8	14.8	13.4	13.4	13.5	13.5	13.5
Total Mineral Soil Flux	(2.3)	(3.4)	(3.0)	(2.9)	(2.9)	(2.9)	(2.9)
Total Organic Soil Flux	0.2	0.3	0.4	0.4	0.4	0.4	0.4
Total Net Flux	10.7	11.8	10.7	10.9	11.0	11.0	11.0

+ Does not exceed 0.05 MMT CO₂ Eq.

Notes: Estimates after 2010 are based on NRI data from 2010 and therefore may not fully reflect changes occurring in the latter part of the time series. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

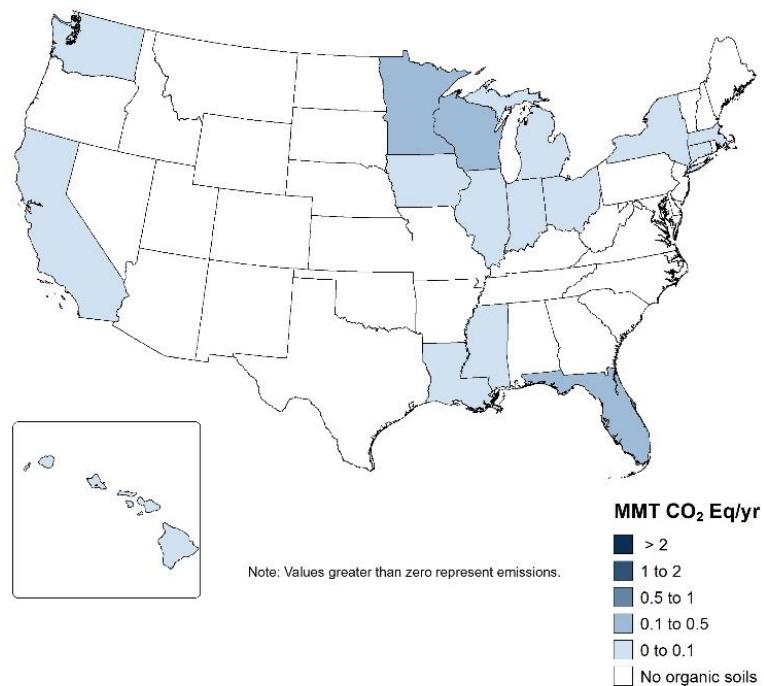
The spatial variability in the 2014 annual flux in CO₂ from mineral soils⁵² is displayed in Figure 6-10 and from organic soils in Figure 6-11. Soil C stocks increased in most states for *Land Converted to Grassland*, which is largely driven by conversion of annual cropland into continuous pasture. The largest gains are in Texas, Missouri and Kentucky. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils used for managed grasslands, including Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and the Pacific Coast.

Figure 6-10: Total Net Annual CO₂ Flux for Mineral Soils under Agricultural Management within States, 2014, *Land Converted to Grassland*



⁵² A planned improvement is to include biomass C stock changes in the figures; currently the maps only include the spatial patterns associated with soil C stock changes.

Figure 6-11: Total Net Annual CO₂ Flux for Organic Soils under Agricultural Management within States, 2014, *Land Converted to Grassland*



Methodology

The following section includes a description of the methodology used to estimate changes in biomass and soil C stocks for *Land Converted to Grassland*, including: (1) loss of aboveground biomass C with conversion of forest to grassland; (2) agricultural land-use and management activities on mineral soils; and (3) agricultural land-use and management activities on organic soils. Belowground live biomass and dead organic matter C stock changes associated with conversion of forest land to grassland are not estimated in the current Inventory for *Land Converted to Grassland*.

Biomass Carbon Stock Changes

A Tier 2 method is applied to estimate aboveground biomass C stock changes⁵³ for *Forest land Converted to Grassland*. For this method, land is stratified by region, forest type, and site productivity and then assigned reference C density estimates for aboveground biomass for the grassland (assumed to be zero since no reference aboveground biomass C density estimates exist) and forest land use. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. Reference C density estimates for aboveground biomass for the forest land use have been estimated from data in the Forest Inventory and Analysis (FIA) program within the USDA Forest Service (USDA Forest Service 2015). If FIA plots include data on individual trees, aboveground C density estimates are based on Woodall et al. (2011), which is also known as the component ratio method, and is a function of tree volume, species, diameter, and, in some regions, height and site quality. See Annex 3.13 for more information about reference C density estimates for forest land.

⁵³ A planned improvement is to estimate the losses of C from belowground biomass, dead wood and litter with *Forest Converted to Grassland*.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Land Converted to Grassland* according to land-use histories recorded in the 2010 USDA NRI survey for non-federal lands (USDA-NRCS 2013). 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 2012 (USDA-NRCS 2015). However, this Inventory only uses NRI data through 2010 because newer data were not available in time to incorporate the additional years. NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2010 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 prior to 1979. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (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 for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils 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 shaly soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

Tier 3 Approach. Mineral SOC stocks and stock changes are estimated using the DAYCENT biogeochemical⁵⁴ 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 2010 USDA NRI survey (USDA-NRCS 2013). C stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2010, but C stock changes from 2010 to 2014 are assumed to be similar to 2010. Future inventories will be updated with new activity data when the data are made available, and the time series will be recalculated (See Planned Improvements section in *Cropland Remaining Cropland*). See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, SOC stock changes are estimated using a Tier 2 Approach for *Land Converted to Grassland* as described in the Tier 2 Approach for mineral soils in the *Grassland Remaining Grassland* section.

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 U.S.-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils.

Uncertainty and Time-Series Consistency

The uncertainty analysis for aboveground biomass C losses with *Forest 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). For additional details see the Uncertainty Analysis in Annex 3.13. Uncertainty analysis for mineral soil 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. The uncertainty for annual C emission estimates from

⁵⁴ Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

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.

Uncertainty estimates are presented in Table 6-42 for each subsource (i.e., biomass C stocks, mineral soil C stocks and organic soil C stocks) 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 total C stocks in *Land Converted to Grassland* ranges from 26 percent below to 27 percent above the 2014 stock change estimate of 40.4 MMT CO₂ Eq.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (MMT CO₂ Eq. and Percent)

Source	2014 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 Grassland	(7.4)	(16.3)	1.4	-119%	+119%
Mineral Soil C Stocks: Tier 3	(7.2)	(15.9)	1.6	-122%	+122%
Mineral Soil C Stocks: Tier 2	(1.4)	(2.2)	(0.8)	-55%	+47%
Organic Soil C Stocks: Tier 2	1.2	0.4	2.3	-63%	+96%
Forests Converted to Grassland	48.7	42.8	54.9	-12%	13%
Biomass C Stocks	49.5	43.7	55.6	-12%	12%
Mineral Soil C Stocks: Tier 2	(0.8)	(1.8)	0.1	-120%	112%
Organic Soil C Stocks: Tier 2	+	+	+	-100%	300%
Other Lands Converted to Grassland	(0.8)	(1.3)	(0.4)	-55%	+47%
Mineral Soil C Stocks: Tier 2	(0.8)	(1.3)	(0.4)	-54%	+46%
Organic Soil C Stocks: Tier 2	+	0.0	+	-100%	+179%
Settlements Converted to Grassland	(0.1)	(0.2)	(+)	-63%	+56%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	(0.1)	-55%	+47%
Organic Soil C Stocks: Tier 2	+	+	+	-79%	+125%
Wetlands Converted to Grasslands	0.1	(0.1)	0.3	-314%	+382%
Mineral Soil C Stocks: Tier 2	(0.2)	(0.4)	(0.1)	-52%	+44%
Organic Soil C Stocks: Tier 2	0.3	0.1	0.5	-51%	+71%
Total: Land Converted to Grassland	40.4	29.8	51.2	-26%	27%
Biomass C Stocks	49.5	43.7	55.6	-12%	12%
Mineral Soil C Stocks: Tier 3	(7.2)	(15.9)	1.6	-122%	122%
Mineral Soil C Stocks: Tier 2	(3.4)	(4.7)	(2.2)	-39%	35%
Organic Soil C Stocks: Tier 2	1.5	0.7	2.6	-50%	77%

^a Absolute value 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.

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

Uncertainty is also associated with lack of reporting non-CO₂ greenhouse gas emissions that occur with biomass burning. Grassland burning is not as common in the United States as in other regions of the world, but fires do occur through both natural ignition sources and prescribed burning. Changes in dead organic matter C stocks are assumed to be negligible in grasslands over annual time frames, although there are likely significant changes at sub-annual time scales across seasons.

Methodological recalculations are applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the above Methodology section.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Methodological recalculations in the current Inventory are associated with the following improvements, including: 1) incorporation of updated NRI data for 1990 through 2010; 2) inclusion of federal grasslands in the Tier 2 analysis; 3) improving the simulation of hydric soils in DAYCENT; and 4) incorporating the aboveground biomass C stock losses with *Forest Land Converted to Grassland*. As a result of these improvements to the Inventory, changes in stocks declined by an average of 49.0 MMT CO₂ Eq. annually over the time series. This represents a 565 percent increase in the losses of carbon with *Land Converted to Grassland* compared to the previous Inventory, and is largely driven by the inclusion of aboveground biomass C loss from *Forest Land Converted to Grasslands* in this category instead of *Forest Land Remaining Forest Land* where it was included in the previous Inventory submissions.

Planned Improvements

Soil C stock changes with land use conversion from forest land to grassland are undergoing further evaluation to ensure consistency in the time series. Different methods are used to estimate soil C stock changes in forest land and grasslands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to grassland. This planned improvement may not be fully implemented for another year, depending on resource availability.

The impact of *Forest Land Converted to Grassland* on belowground biomass and dead organic matter pools are not estimated in the current Inventory, and so another planned improvement is to estimate changes in C stocks for these pools in the next Inventory. 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.

One additional planned improvement for the *Land Converted to Grassland* category is to develop an inventory of C stock changes for grasslands in Alaska. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

6.8 Wetlands Remaining Wetlands (IPCC Source Category 4D1)

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands which 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, and abandonment, restoration, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of harvested peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH₄ and N₂O, however, this is a very small component of total emissions from this source category in the United States. The natural production of CH₄ 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 CH₄ flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under 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. This Inventory estimates CO₂, N₂O, and CH₄ emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO₂, N₂O, and CH₄ Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO₂, N₂O, and CH₄ 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 CO₂ emissions from *Peatlands Remaining Peatlands* using the Tier 1 approach. Current methodologies estimate only on-site N₂O and CH₄ emissions, since off-site N₂O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH₄ 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 CO₂ is emitted from the oxidation of the peat. Since N₂O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N₂O 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 N₂O, and contributes to the activity of methanogens, which produce CH₄, and methanotrophs which oxidize CH₄ into CO₂ (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Ditch networks, which are constructed in order to drain the water off in preparation for peat extraction, also contribute to the flux of CH₄ through *in situ* production and lateral transfer of CH₄ from the organic soil matrix (IPCC 2013).

The two sources of off-site CO₂ emissions from managed peatlands are waterborne carbon losses and the horticultural and landscaping use of peat. Drainage waters in peatlands accumulate dissolved organic carbon which then reacts within aquatic ecosystems and is converted to CO₂ where it is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). Most (nearly 98 percent) of the CO₂ emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for horticultural and landscaping purposes. 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.

Total emissions from *Peatlands Remaining Peatlands* were estimated to be 0.8 MMT CO₂ Eq. in 2014 (see Table 6-43) comprising 0.8 MMT CO₂ Eq. (842 kt) of CO₂, 0.001 MMT CO₂ Eq. (0.002 kt) of N₂O, and 0.004 MMT CO₂ Eq. (0.17 kt) of CH₄. Total emissions in 2014 were about 9 percent larger than total emissions in 2013. Peat production in Alaska in 2014 was not reported in *Alaska's Mineral Industry 2013* report. However, peat production reported in the lower 48 states in 2014 was 10 percent more than in 2013, and as a result, the emissions from *Peatlands Remaining Peatlands* in the lower 48 states and Alaska were greater in 2014 compared to 2013.

Total emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO₂ Eq. across the time series with a decreasing trend from 1990 until 1993 followed by an increasing trend through 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009, when the trend reversed until a slight increase from 2013 to 2014. Carbon dioxide emissions from *Peatlands Remaining Peatlands* have fluctuated between 0.8 and 1.3 MMT CO₂ across the time series, and these emissions drive the trends in total emissions. CH₄ and N₂O emissions remained close to zero across the time series.

Table 6-43: Emissions from Peatlands Remaining Peatlands (MMT CO₂ Eq.)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	1.1	1.1	1.0	0.9	0.8	0.8	0.8
Off-site	1.0	1.0	1.0	0.9	0.8	0.7	0.8

On-site	0.1		0.1		0.1		0.1	
N ₂ O (On-site)	+		+		+		+	
CH ₄ (On-site)	+		+		+		+	
Total	1.1		1.1		1.0		0.9	

+ Does not exceed 0.05 MMT CO₂ Eq.

Notes: 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 N₂O emissions are not estimated to avoid double-counting N₂O 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.

Table 6-44: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2010	2011	2012	2013	2014
CO ₂	1,055	1,101	1,022	926	812	770	842
Off-site	985	1,030	956	866	760	720	787
On-site	70	71	66	60	53	50	55
N ₂ O (On-site)	+	+	+	+	+	+	+
CH ₄ (On-site)	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

Notes: 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 N₂O emissions are not estimated to avoid double-counting N₂O 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.

Methodology

Off-site CO₂ Emissions

Off-site CO₂ emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). The emissions were calculated by apportioning the annual weight of peat produced in the United States (Table 6-45) 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 CO₂ 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 1995–2015a; USGS 2015b). 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 1997–2014). 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 6-46). However, volume production data were used to calculate off-site CO₂ emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors

from IPCC (2006).⁵⁵ Peat production was not reported for 2014 in *Alaska's Mineral Industry 2013* report (DGGS 2014); therefore Alaska's peat production in 2014 (reported in cubic yards) was assumed to be equal to its peat production in 2013.

Consistent with IPCC (2013) guidelines, off-site CO₂ emissions from dissolved organic carbon transported off-site 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 CO₂ 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 two-and-a-half times 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 CO₂ 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; from 2010 to 2013, imports of sphagnum moss (nutrient-poor) peat from Canada represented 63 percent of total U.S. peat imports (USGS 2015c). 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 CO₂ 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 6-45: Peat Production of Lower 48 States (kt)

Type of Deposit	1990	2005	2010	2011	2012	2013	2014
Nutrient-Rich	595.1	657.6	558.9	511.2	409.9	418.5	459.0
Nutrient-Poor	55.4	27.4	69.1	56.8	78.1	46.5	51.0
Total Production	692.0	685.0	628.0	568.0	488.0	465.0	510.0

Sources: United States Geological Survey (USGS) (1991–2015a) *Minerals Yearbook: Peat* (1994–2014); United States Geological Survey (USGS) (2015b) *Mineral Commodity Summaries: Peat* (2014).

Table 6-46: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2010	2011	2012	2013	2014
Total Production	49.7	47.8	59.8	61.5	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2014) *Alaska's Mineral Industry Report* (1997–2013).

On-site CO₂ 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 in accordance with IPCC (2006), an average production rate per area 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).⁵⁶ In the lower 48 states, the area of land managed for peat extraction 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. The nutrient-rich and nutrient-poor annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO₂ emission estimates. Production data are not available by weight for Alaska. In order to calculate on-site

⁵⁵ 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).

⁵⁶ 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).

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 same assumption that a single hectare yields 100 metric tons. The IPCC (2006) on-site emissions equation also includes a term which 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 methodologies (IPCC 2006 and 2013).

On-site N₂O Emissions

IPCC (2006) suggests basing the calculation of on-site N₂O 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 CO₂ emissions methodology above details the calculation of area data from production data. In order to estimate N₂O emissions, the area of nutrient rich *Peatlands Remaining Peatlands* was multiplied by the appropriate default emission factor taken from IPCC (2013).

On-site CH₄ Emissions

IPCC (2013) also suggests basing the calculation of on-site CH₄ 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 CO₂ Emissions section above. In order to estimate CH₄ emissions from drained land surface, the area of *Peatlands Remaining Peatlands* was multiplied by the emission factor for direct CH₄ emissions taken from IPCC (2013). In order to estimate CH₄ 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).

Uncertainty and Time-Series Consistency

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO₂, CH₄, and N₂O emissions from *Peatlands Remaining Peatlands*, 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 6-47. Carbon dioxide emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.7 and 1.0 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of 14 percent below to 19 percent above the 2014 emission

estimate of 0.8 MMT CO₂ Eq. Methane emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.002 and 0.008 MMT CO₂ Eq. This indicates a range of 62 percent below to 61 percent above the 2014 emission estimate of 0.005 MMT CO₂ Eq. Nitrous oxide emissions from *Peatlands Remaining Peatlands* in 2014 were estimated to be between 0.0003 and 0.0010 MMT CO₂ Eq. at the 95 percent confidence level. This indicates a range of 51 percent below to 61 percent above the 2014 emission estimate of 0.0006 MMT CO₂ Eq.

Table 6-47: Approach 2 Quantitative Uncertainty Estimates for CO₂, CH₄, and N₂O Emissions from *Peatlands Remaining Peatlands* (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO ₂	0.8	0.7	1.0	-14%	+19%	
Peatlands Remaining Peatlands	CH ₄	+	+	+	-62%	+61%	
Peatlands Remaining Peatlands	N ₂ O	+	+	+	-51%	+61%	

+ Does not exceed 0.05 MMT CO₂ 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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation and no issues were identified.

Recalculations Discussion

The emission estimates for *Peatlands Remaining Peatlands* were updated for 2014 using the Peat section of the *Mineral Commodity Summaries 2015*. The new edition provided 2014 data for the lower 48 states, but data for Alaska were still unavailable. Because no peat production has been reported since *Alaska's Mineral Industry 2012* report, the 2013 and 2014 values were assumed to be equal to the 2012 value. 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 CO₂, N₂O, and CH₄ emissions from *Peatlands Remaining Peatlands*, future efforts will investigate if data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

The *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* describes inventory methodologies for various wetland source categories. In the 1990 through 2013 Inventory, updated methods for *Peatlands Remaining Peatlands* to align them with the *IPCC Supplement* were begun to be incorporated. For future inventories, the need for additional updates will be evaluated, in order to further address the IPCC Supplement for *Peatlands Remaining Peatlands*.

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* (IPCC 2013) 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 reports.

Box 6-6: Progress on Inclusion of Managed Coastal Wetlands in the U.S. Greenhouse Gas Inventory

In 2014, the IPCC released the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement)*. The *Wetlands Supplement* provides methods for estimating anthropogenic emissions and removals of greenhouse gases from wetlands and drained soils. Specific consideration is given here to the inclusion of coastal wetlands as part of LULUCF reporting for anthropogenic emissions and removals of CO₂ and CH₄ and N₂O emissions.

In preparation for the next submission of the U.S. Inventory, the United States is exploring methodological approaches based on guidance in the *Wetlands Supplement*. The goal is to assemble all necessary activity data and emission factors, implement the methods described in the *Wetlands Supplement* and generate estimates at the Tier 1 or 2 level for managed coastal wetlands in the conterminous United States.

Fundamental considerations for inclusion of coastal wetlands as part of LULUCF reporting are: (1) how to apply the guidance in the *Wetlands Supplement* to specify what coastal wetlands are managed; (2) understanding what land-use categories coastal wetlands are in (i.e., Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land) and ensuring there is no overlap or missing lands within the U.S. land use matrix; and (3) understanding how the guidance can be applied when significant greenhouse gas emissions and removals occur in managed coastal wetlands outside of the U.S. land use matrix (i.e., seagrass meadows). These issues are under consideration and review by an interagency (U.S. Government) and academic team in anticipation of the next submission of the U.S. Inventory.

The availability of data and resources will be primary drivers in determining how the approaches in the *Wetlands Supplement* are applied. Specifically, the United States will work toward developing its inventory reporting of greenhouse gas emissions and removals from coastal wetlands by: (1) obtaining, collating and refining land use and land-use change data including (a) creating the coastal wetland boundary, (b) recognizing management activities and coastal wetland change resulting in land-use conversion (c) creating seamless integration where coastal wetlands may overlap with other land-use categories, (d) distinguishing salinity levels and soil types to apply appropriate C stocks and emission factors; and (2) developing the sector-specific inventory report for each new category and sub-category by: (a) increasing efforts toward reconciling land cover and land cover change spatial databases (i.e., Coastal Change Analysis Program) with vegetation, soil C stock and stock change data, and other levels of disaggregation that improve estimation accuracy, (b) developing Tier 1 (or Tier 2, if activity data and emission factors are available) emissions estimates for new source/sink categories under Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land, and (c) developing Tier 1 (or Tier 2, if activity data and emission factors are available) estimates of new source/sink categories that fall under new subcategories under Wetlands (*Other Wetlands Remaining Other Wetlands* and *Land Converted to Other Wetlands*) from the following activities: i) forest management in mangroves, ii) extraction in mangroves, tidal marshes and seagrass meadows (including excavation, aquaculture and salt production), iii) rewetting, revegetation and creation in mangroves, tidal marshes and seagrass meadows, iv) soil drainage in mangroves and tidal marshes (CO₂) and v) new categories of CH₄ emissions from rewetting of mangroves and tidal marshes and N₂O emissions from aquaculture, and (d) developing QA/QC procedures and protocols to be used in generating the estimates, and (e) refining uncertainty estimates.

6.9 Land Converted to Wetlands (IPCC Source Category 4D2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to wetlands each year, just as wetlands are converted to other uses. While the magnitude of these area changes is known (see Table 6-7), research is ongoing to track greenhouse gas fluxes across *Wetlands Remaining Wetlands* and *Land Converted to Wetlands*. Until such time that reliable and comprehensive estimates of greenhouse gas fluxes across these land-use and land-use change categories can be produced, it is not possible to separate CO₂, CH₄ or N₂O fluxes on *Land Converted to Wetlands* from fluxes on *Wetlands Remaining Wetlands* at this time.

6.10 Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 4E1)

Urban forests constitute a significant portion of the total U.S. tree canopy cover (Dwyer et al. 2000). Urban areas (cities, towns, and villages) are estimated to cover over 3 percent of the United States (U.S. Census Bureau 2012). With an average tree canopy cover of 35 percent, urban areas account for approximately 5 percent of total tree cover in the continental United States (Nowak and Greenfield 2012). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 76.4 MMT CO₂ Eq. (20.8 MMT C) over the period from 1990 through 2014. Net C flux from urban trees in 2014 was estimated to be −90.6 MMT CO₂ Eq. (−24.7 MMT C). Annual estimates of CO₂ flux (Table 6-48) were developed based on periodic (1990, 2000, and 2010) U.S. Census data on urbanized area. The estimate of urbanized area is smaller than the area categorized as *Settlements* in the Representation of the U.S. Land Base section developed for this report: over the 1990 through 2014 time series the Census urban area totaled, on average, about 63 percent of the *Settlements* area.

In 2014, Census urban area totaled about 68 percent of the total area defined as *Settlements*. Census area data are preferentially used to develop C flux estimates for this source category since these data are more applicable for use with the available peer-reviewed data on urban tree canopy cover and urban tree C sequestration. Annual sequestration increased by 50 percent between 1990 and 2014 due to increases in urban land area. Data on C storage and urban tree coverage were collected since the early 1990s and have been applied to the entire time series in this report. As a result, the estimates presented in this chapter are not truly representative of changes in C stocks in urban trees for *Settlements* areas, but are representative of changes in C stocks in urban trees for Census urban area. The method used in this report does not attempt to scale these estimates to the *Settlements* area. Therefore, the estimates presented in this chapter are likely an underestimate of the true changes in C stocks in urban trees in all *Settlements* areas—i.e., the changes in C stocks in urban trees presented in this chapter are a subset of the changes in C stocks in urban trees in all *Settlements* areas.

Urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). Because tree density in urban areas is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for urban areas than for forest areas. To quantify the C stored in urban 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 forests). Expressed in this way per unit of tree cover, areas covered by urban trees actually have a greater C density than do forested areas (Nowak and Crane 2002). Expressed per unit of land area, however, the situation is the opposite: because tree density is so much lower in urban areas, these areas have a smaller C density per unit land area than forest areas.

Table 6-48: Net C Flux from Urban Trees (MMT CO₂ Eq. and MMT C)

Year	MMT CO ₂ Eq.	MMT C
1990	(60.4)	(16.5)
2005	(80.5)	(22.0)
2010	(86.1)	(23.5)
2011	(87.3)	(23.8)
2012	(88.4)	(24.1)
2013	(89.5)	(24.4)
2014	(90.6)	(24.7)

Note: Parentheses indicate net sequestration.

Methodology

Methods for quantifying urban 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, the methodology used by Nowak et al. (2013) to estimate net C sequestration in urban trees followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and states were used to develop allometric equations that are then used to estimate C in urban tree biomass from data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, land-use class, and growing season to generate estimates of gross C sequestration in urban 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 values to derive estimates of net C sequestration.

For this Inventory report, net C sequestration estimates for all 50 states and the District of Columbia, that were generated using the Nowak et al. (2013) methodology and expressed in units of C sequestered per unit area of tree cover, were then used to estimate urban tree C sequestration in the United States. To accomplish this, we used urban area estimates from U.S. Census data together with urban tree cover percentage estimates for each state and the District of Columbia from remote sensing data, an approach consistent with Nowak et al. (2013).

This approach is also 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 urban 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).

The first step in the methodology is to develop allometric equations that can be used to estimate C in urban tree biomass. In order to generate these allometric relationships between tree dimensions and tree biomass for cities and states, Nowak et al. (2013) and previously published research (Nowak and Crane 2002; Nowak 1994, 2007b, 2009) collected field measurements in a number of U.S. cities between 1989 and 2012. For a sample of trees in representative cities, data including tree measurements of stem diameter, tree height, crown height and crown width, and information on location, species, and canopy condition were collected. The data for each tree were converted into C storage by applying allometric equations to estimate aboveground biomass, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, moisture content, a C content of 50 percent (dry weight basis), and an adjustment factor of 0.8 to account for urban trees having less aboveground biomass for a given stem diameter than predicted by allometric equations based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. These calculations were then used to develop an allometric equation relating tree dimensions to C storage for each species of tree, encompassing a range of diameters.

The second step in the methodology is to estimate rates of tree growth for urban trees in the United States. Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. In the Nowak et al. (2013) methodology that is applied here, growth calculations were adjusted by a factor to account for tree condition (fair to excellent, poor, critical, dying, or dead). For each tree, 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 species (or genus), diameter class, and land-use condition (e.g., parks, transportation, vacant, golf courses) were then scaled up to city estimates using tree population information. 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 (Nowak 2011).

Most of the field data used to develop the methodology of Nowak et al. (2013) were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model. UFORE is a computer model that uses standardized field data from random plots in each city and local air pollution and meteorological data to quantify urban forest structure, values of the urban forest, and environmental effects, including total C stored and annual C sequestration. UFORE was used with field data from a stratified random sample of plots in each city to quantify the characteristics of the urban forest (Nowak et al. 2007).

Where gross C sequestration accounts for all carbon sequestered, net C sequestration for urban trees takes into account C emissions associated with tree death and removals. In the third step in the methodology developed by Nowak et al. (2013), estimates of net C emissions from urban trees were derived by applying estimates of annual mortality and condition, and assumptions about whether dead trees were removed from the site to the total C stock estimate for each city. Estimates of annual mortality rates by diameter class and condition class were derived 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. The estimated annual gross C emission rates for each species (or genus), diameter class, and condition class were then scaled up to city estimates using tree population information.

The data for all 50 states and the District of Columbia are described in Nowak et al. (2013) and reproduced in Table 6-49, which builds upon previous research, including: Nowak and Crane (2002), Nowak et al. (2007), Nowak and Greenfield (2012), and references cited therein. The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric equations applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994 and Nowak et al. 2002), but if no allometric equation could be found for the particular species, the average result for the genus was used. The adjustment (0.8) to account for less live tree biomass in 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 (BG) 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 health and 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 6-49) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state urban area and urban 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 U.S. Census data.

Specifically, urban area estimates were based on 1990, 2000, and 2010 U.S. Census data. The 1990 U.S. Census defined urban land as "urbanized areas," which included land with a population density greater than 1,000 people per square mile, and adjacent "urban places," which had predefined political boundaries and a population total greater than 2,500. In 2000, the U.S. Census replaced the "urban places" category with a new category of urban land called an "urban cluster," which included areas with more than 500 people per square mile. In 2010, the Census updated its definitions to have "urban areas" encompassing Census tract delineated cities with 50,000 or more people, and "urban clusters" containing Census tract delineated locations with between 2,500 and 50,000 people. Urban land area increased by approximately 23 percent from 1990 to 2000 and 14 percent from 2000 to 2010; Nowak et al. (2005) estimate that the changes in the definition of urban land are responsible for approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under all Census (i.e., 1990, 2000, and 2010) definitions, the urban category encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). *Settlements* area, as assessed in the Representation of the U.S. Land Base section developed for this report, encompassed all developed parcels greater than 0.1 hectares in size, including rural transportation corridors, and as previously mentioned represents a larger area than the Census-derived urban area estimates.

However, the smaller, Census-derived urban area estimates were deemed to be more suitable for estimating national urban tree cover given the data available in the peer-reviewed literature (i.e., the data set available is consistent with Census urban rather than *Settlements* areas), and the recognized overlap in the changes in C stocks between urban forest and non-urban forest (see Planned Improvements below). U.S. Census urban area data is reported as a series of continuous blocks of urban area in each state. The blocks or urban area were summed to create each state's urban area estimate.

Net annual C sequestration estimates were derived for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.74, the standard ratio for net/gross sequestration set out in Table 3 of Nowak et al. (2013) (unless data existed for both gross and net sequestration for the state in Table 2 of Nowak et al. (2013), in which case they were divided to get a state-specific ratio). The gross and net annual C sequestration values for each state were multiplied by each state's area of tree cover, which was the product of the state's urban/community area as defined in the U.S. Census (2012) and the state's urban/community tree cover percentage. The urban/community

tree cover percentage estimates for all 50 states were obtained from Nowak and Greenfield (2012), which compiled ten years of research including Dwyer et al. (2000), Nowak et al. (2002), Nowak (2007a), and Nowak (2009). The urban/community tree cover percentage estimate for the District of Columbia was obtained from Nowak et al. (2013). The urban area estimates were taken from the 2010 U.S. Census (2012). The equation, used to calculate the summed carbon sequestration amounts, can be written as follows:

$$\text{Net annual C sequestration} = \text{Gross sequestration rate} \times \text{Net to Gross sequestration ratio} \times \text{Urban Area} \times \% \text{ Tree Cover}$$

Table 6-49: Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m²-yr) for 50 states plus the District of Columbia (2014)

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	1,165,574	862,524	55.2	0.343	0.254	0.74
Alaska	44,744	33,111	39.8	0.168	0.124	0.74
Arizona	385,644	285,376	17.6	0.354	0.262	0.74
Arkansas	424,922	314,443	42.3	0.331	0.245	0.74
California	2,106,024	1,558,458	25.1	0.389	0.288	0.74
Colorado	153,806	113,817	18.5	0.197	0.146	0.74
Connecticut	771,006	570,544	67.4	0.239	0.177	0.74
Delaware	136,070	100,692	35.0	0.335	0.248	0.74
DC	14,559	11,569	35.0	0.263	0.209	0.79
Florida	3,429,742	2,538,009	35.5	0.475	0.352	0.74
Georgia	2,580,659	1,909,688	54.1	0.353	0.261	0.74
Hawaii	246,168	182,164	39.9	0.581	0.430	0.74
Idaho	25,533	18,894	10.0	0.184	0.136	0.74
Illinois	760,263	562,594	25.4	0.283	0.209	0.74
Indiana	406,015	375,425	23.7	0.250	0.231	0.92
Iowa	119,006	88,064	19.0	0.240	0.178	0.74
Kansas	186,077	144,799	25.0	0.283	0.220	0.78
Kentucky	243,641	180,295	22.1	0.286	0.212	0.74
Louisiana	749,632	554,727	34.9	0.397	0.294	0.74
Maine	108,092	79,988	52.3	0.221	0.164	0.74
Maryland	597,897	442,444	34.3	0.323	0.239	0.74
Massachusetts	1,309,649	969,140	65.1	0.254	0.188	0.74
Michigan	740,048	547,635	35.0	0.220	0.163	0.74
Minnesota	354,139	262,063	34.0	0.229	0.169	0.74
Mississippi	494,558	365,973	47.3	0.344	0.255	0.74
Missouri	498,925	369,205	31.5	0.285	0.211	0.74
Montana	53,940	39,916	36.3	0.184	0.136	0.74
Nebraska	50,920	42,970	15.0	0.238	0.201	0.84
Nevada	44,096	32,631	9.6	0.207	0.153	0.74
New Hampshire	250,531	185,393	66.0	0.217	0.161	0.74
New Jersey	1,201,070	888,792	53.3	0.294	0.218	0.74
New Mexico	70,002	51,801	12.0	0.263	0.195	0.74
New York	1,096,654	811,524	42.6	0.240	0.178	0.74
North Carolina	2,076,636	1,536,711	51.1	0.312	0.231	0.74
North Dakota	14,946	7,102	13.0	0.223	0.106	0.48
Ohio	927,316	686,214	31.5	0.248	0.184	0.74
Oklahoma	366,160	270,959	31.2	0.332	0.246	0.74
Oregon	261,067	193,190	36.6	0.242	0.179	0.74
Pennsylvania	1,264,702	935,879	41.0	0.244	0.181	0.74
Rhode Island	137,147	101,489	51.0	0.258	0.191	0.74
South Carolina	1,107,882	819,832	48.9	0.338	0.250	0.74
South Dakota	21,348	18,513	14.0	0.236	0.205	0.87
Tennessee	1,063,362	950,771	43.8	0.303	0.271	0.89
Texas	2,808,539	2,078,319	31.4	0.368	0.272	0.74
Utah	91,713	67,868	16.4	0.215	0.159	0.74

Vermont	46,571	34,462	53.0	0.213	0.158	0.74
Virginia	839,610	621,311	39.8	0.293	0.217	0.74
Washington	571,062	422,586	34.6	0.258	0.191	0.74
West Virginia	255,369	188,973	61.0	0.241	0.178	0.74
Wisconsin	364,611	269,812	31.8	0.225	0.167	0.74
Wyoming	19,203	14,210	19.9	0.182	0.135	0.74
Total	33,056,852	24,712,872				

Uncertainty and Time-Series Consistency

Uncertainty associated with changes in C stocks in urban trees includes the uncertainty associated with urban area, percent urban tree coverage, 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 urban area estimates based on expert judgment. Uncertainty associated with estimates of percent urban tree coverage for each of the 50 states was based on standard error estimates reported by Nowak and Greenfield (2012). Uncertainty associated with estimate of percent urban tree coverage for the District of Columbia was based on the standard error estimate reported by Nowak et al. (2013). 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 reported by Nowak et al. (2013). 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 equations, 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 may be some overlap between the urban tree C estimates and the forest tree C estimates. Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of urban 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. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-50. The net C flux from changes in C stocks in urban trees in 2014 was estimated to be between -134.0 and -47.4 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 51 percent more sequestration to 46 percent less sequestration than the 2014 flux estimate of -90.6 MMT CO₂ Eq.

Table 6-50: Approach 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Changes in C Stocks in Urban Trees	CO ₂	(90.6)	(134.0)	(47.4)	-51%	+46%

^a Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

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 2014. 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 urban 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. One key edit in the current Inventory report is that Table 6-49 has been updated. For this Table, the values in the 1990 through 2012 Inventory and 1990 through 2013 Inventory reports were the same. The updated

values for the current (1990 through 2014) Inventory were inserted here, noting that they represent a two-year increment in urban tree C sequestration from what was presented in the previous Inventory.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in the Representation of the U.S. Land Base section, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between urban forest and non-urban forest greenhouse gas inventories. Because some plots defined as “forest” in the Forest Inventory and Analysis (FIA) program of the USDA Forest Service actually fall within the boundaries of the areas also defined as Census urban, there may be “double-counting” of these land areas in estimates of C stocks and fluxes for this report. Specifically, 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 Trees source category.

Future research may also enable more complete coverage of changes in the C stock in urban trees for all *Settlements* land. To provide estimates for all *Settlements*, research would need to establish the extent of overlap between the areas of land included in the *Settlements* land use category and Census-defined urban areas, and would have to separately characterize sequestration on non-urban *Settlements* land.

N₂O Fluxes from Settlement Soils (IPCC Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 3.1 percent are currently applied to lawns, golf courses, and other landscaping occurring within settlement areas. Application rates are lower than those occurring on cropped soils, and, therefore, account for a smaller proportion of total U.S. soil N₂O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface applied sewage sludge is applied to settlement areas.

N additions to soils result in direct and indirect N₂O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer and sludge N that is transformed and transported to another location in a form other than N₂O (ammonia [NH₃] and nitrogen oxide [NO_x] volatilization, nitrogen trioxide [NO₃] leaching and runoff), and later converted into N₂O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N₂O emissions from settlement soils were 2.4 MMT CO₂ Eq. (8 kt of N₂O) in 2014. There was an overall increase of 78 percent from 1990 to 2014 due to an expanding settlement area requiring more synthetic N fertilizer. Interannual variability in these emissions is directly attributable to interannual variability in total synthetic fertilizer consumption and sewage sludge applications in the United States. Emissions from this source are summarized in Table 6-51.

Table 6-51: N₂O Fluxes from Soils in *Settlements Remaining Settlements* (MMT CO₂ Eq. and kt N₂O)

	1990	2005	2010	2011	2012	2013	2014
Direct N₂O Fluxes from Soils							
MMT CO ₂ Eq.	1.0	1.8	1.8	1.9	1.9	1.8	1.8
kt N ₂ O	3	6	6	6	6	6	6
Indirect N₂O Fluxes from Soils							
MMT CO ₂ Eq.	0.4	0.6	0.6	0.6	0.6	0.6	0.6
kt N ₂ O	1	2	2	2	2	2	2
Total							
MMT CO ₂ Eq.	1.4	2.3	2.4	2.5	2.5	2.4	2.4
kt N ₂ O	5	8	8	8	9	8	8

Note: Totals may not sum due to independent rounding.

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach is used to estimate soil N₂O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N₂O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, and the amount of N in

sewage sludge applied to non-agricultural land and surface disposal (see Annex 3.12 for a detailed discussion of the methodology for estimating sewage sludge application).

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Ruddy et al. 2006). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2002 through 2014 are based on 2001 values adjusted for annual total N fertilizer sales in the United States because there is no new activity data on application after 2001. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications are derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.12 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 N₂O emissions (IPCC 2006).

For indirect emissions, the total N applied from fertilizer and sludge 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 N₂O 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 N₂O off-site. The resulting estimates are summed to obtain total indirect emissions.

Uncertainty and Time-Series Consistency

The amount of N₂O emitted from settlements 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 irrigation/watering practices. The effect of the combined interaction of these variables on N₂O flux is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variations in fertilizer N and sewage sludge application rates. All settlement soils are treated equivalently under this methodology.

Uncertainties exist in both the fertilizer N and sewage sludge application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ± 50 percent.⁵⁷ Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal is derived from variability in several factors, including: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal. In addition, the uncertainty ranges around 2005 activity data and emission factor input variables are directly applied to the 2014 emission estimates. Uncertainty in the direct and indirect emission factors is provided by IPCC (2006).

Uncertainty is quantified using simple error propagation methods (IPCC 2006), and the results are summarized in Table 6-52. Direct N₂O emissions from soils in *Settlements Remaining Settlements* in 2014 are estimated to be between 0.9 and 4.8 MMT CO₂ Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2014 emission estimate of 1.8 MMT CO₂ Eq. Indirect N₂O emissions in 2014 are between 0.1 and 1.9 MMT CO₂ Eq., ranging from a -85 percent to 212 percent around the estimate of 0.6 MMT CO₂ Eq.

Table 6-52: Quantitative Uncertainty Estimates of N₂O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emissions (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements:						
Direct N ₂ O Fluxes from Soils	N ₂ O	1.8	0.9	4.8	-49%	+163%
Indirect N ₂ O Fluxes from Soils	N ₂ O	0.6	0.1	1.9	-85%	+212%

Note: These estimates include direct and indirect N₂O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

⁵⁷ No uncertainty is provided with the USGS fertilizer consumption data (Ruddy et al. 2006) so a conservative ± 50 percent is used in the analysis.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

The spreadsheet containing fertilizer and sewage sludge applied to settlements and calculations for N₂O and uncertainty ranges have been checked and verified.

Planned Improvements

A minor improvement is planned to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

6.11 Land Converted to Settlements (IPCC Source Category 4E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO₂ or N₂O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

6.12 Other Land Remaining Other Land (IPCC Source 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 6-7), 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 CO₂ or N₂O fluxes on *Other Land Remaining Other Land* at this time.

6.13 Land Converted to Other Land (IPCC Source 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 6-7), 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 CO₂, CH₄ or N₂O fluxes on *Land Converted to Other Land* from fluxes on *Other Land Remaining Other Land* at this time.

6.14 Other (IPCC Source Category 4H)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

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 are associated with particular land uses. For example, harvested wood products are accounted for under *Forest Land Remaining Forest Land* because these wood products are considered a component of the forest ecosystem. The wood products serve as reservoirs to which C resulting from photosynthesis in trees is transferred, but the removals in this case occur in the forest. Carbon stock changes in yard trimmings and food scraps are associated with settlements, but removals in this case do not occur within settlements. To address this complexity, yard trimming and food scrap C storage is reported under the “Other” source category.

Both the amount of yard trimmings collected annually and the fraction that is landfilled have declined over the last decade. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps were generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2015a). 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 2.3 percent decrease in the tonnage of yard trimmings generated (i.e., collected for composting or disposal). 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 32 percent in 2014. The net effect of the reduction in generation and the increase in composting is a 57 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by 55 percent since 1990, and though the proportion of food scraps discarded in landfills has decreased slightly from 82 percent in 1990 to 76 percent in 2014, the tonnage disposed of in landfills has increased considerably (by 45 percent). Although the total tonnage of food scraps disposed in landfills has increased from 1990 to 2014, the annual carbon stock net changes from food scraps have decreased (as shown in Table 6-53 and Table 6-54), due to smaller annual differences in the amount of food waste disposed in landfills. 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 landfill C storage from 26.0 MMT CO₂ Eq. (7.1 MMT C) in 1990 to 11.6 MMT CO₂ Eq. (3.2 MMT C) in 2014 (Table 6-53 and Table 6-54).

Table 6-53: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT CO₂ Eq.)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Yard Trimmings	(21.0)	(7.4)	(9.3)	(9.2)	(9.1)	(8.5)	(8.5)
Grass	(1.8)	(0.6)	(0.9)	(0.9)	(0.9)	(0.8)	(0.8)
Leaves	(9.0)	(3.4)	(4.2)	(4.2)	(4.2)	(3.9)	(3.9)
Branches	(10.2)	(3.4)	(4.1)	(4.1)	(4.1)	(3.8)	(3.8)
Food Scraps	(5.0)	(4.0)	(3.9)	(3.5)	(3.1)	(3.2)	(3.1)
Total Net Flux	(26.0)	(11.4)	(13.2)	(12.7)	(12.2)	(11.7)	(11.6)

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

Table 6-54: Net Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Yard Trimmings	(5.7)	(2.0)	(2.5)	(2.5)	(2.5)	(2.3)	(2.3)
Grass	(0.5)	(0.2)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)

Leaves	(2.5)	(0.9)	(1.2)	(1.1)	(1.1)	(1.1)	(1.1)
Branches	(2.8)	(0.9)	(1.1)	(1.1)	(1.1)	(1.0)	(1.0)
Food Scraps	(1.4)	(1.1)	(1.1)	(1.0)	(0.9)	(0.9)	(0.8)
Total Net Flux	(7.1)	(3.1)	(3.6)	(3.5)	(3.3)	(3.2)	(3.2)

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 terrestrial 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, based on methodologies presented for the Land Use, Land-Use Change, and Forestry sector in IPCC (2003). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings or 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 that decomposed.

To determine the total landfilled C stocks for a given year, the following were estimated: (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 2013* (EPA 2015a), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2009 and 2011 through 2013. To provide data for some of the missing years, detailed backup data were obtained from historical data tables that EPA developed for 1960 through 2013 (EPA 2015b). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Data for 2014 are not yet available, so they were set equal to 2013 values. The EPA (2015a) report and historical data tables (EPA 2015b) do not subdivide the discards (i.e., total generated minus composted) of individual materials into masses landfilled and combusted, although it provides a mass of overall waste stream discards managed in landfills⁵⁸ and combustors with energy recovery (i.e., ranging from 67 percent and 33 percent, respectively, in 1960 to 92 percent and 8 percent, respectively, in 1985); it is assumed that the proportion of each individual material (food scraps, grass, leaves, branches) that is landfilled is the same as the proportion across the overall waste stream.

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 as cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-55).

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

⁵⁸ EPA (2015a and 2015b) reports discards in two categories: “combustion with energy recovery” and “landfill, other disposal,” which includes combustion without energy recovery. For years in which there is data from previous EPA reports on combustion without energy recovery, EPA assumes these estimates are still applicable. For 2000 to present, EPA assumes that any combustion of MSW that occurs includes energy recovery, so all discards to “landfill, other disposal” are assumed to go to landfills.

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 (Percent)” in Table 6-55).

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 CH₄ and CO₂. (The CH₄ emissions resulting from decomposition of yard trimmings and food scraps are accounted for 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 6-55.

The first-order decay rates, k , for each refuse type were 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 found 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, 1990 waste composition for the United States from EPA’s *Characterization of Municipal Solid Waste in the United States: 1990 Update* was used to calculate f . This correction factor is then multiplied 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 found, including dry conditions (less than 25 inches of rain annually, $k=0.02$) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, $k=0.12$). As in Section 7.1 Landfills (which estimates CH₄ 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, the correction factors (f) were developed for decay rates of 0.038 and 0.057 year⁻¹ through linear interpolation. A weighted national average component-specific decay rate was 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 component-specific decay rates are shown in Table 6-55.

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:

$$LFC_{i,t} = \sum_n^t W_{i,n} \times (1 - MC_i) \times ICC_i \times \{ [CS_i \times ICC] + [(1 - (CS_i \times ICC)) \times e^{-k(t-n)}] \}$$

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 Equation 2 as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{(t-1)}$$

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 (2014). For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C. 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 (518,000 metric tons) decomposes, leaving a total of 617,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2014, 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 2014), the total landfill C from food scraps in 2014 was 41.5 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 2014, yielding a value of 264.7 million metric tons (as shown in Table 6-56). In exactly 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 6-54) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2014 shown in Table 6-54 (3.2 MMT C) is equal to the stock in 2014 (264.7 MMT C) minus the stock in 2013 (261.5 MMT C).

The C stocks calculated through this procedure are shown in Table 6-56.

Table 6-55: 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 ₂ O)	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)	0.323	0.185	0.016	0.156

Table 6-56: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2010	2011	2012	2013	2014
Yard Trimmings	155.8	202.9	213.6	216.1	218.6	220.9	223.2
Grass	14.5	18.1	19.0	19.3	19.5	19.7	20.0
Leaves	66.7	87.3	92.2	93.4	94.5	95.6	96.6
Branches	74.6	97.5	102.3	103.4	104.5	105.6	106.6
Food Scraps	17.6	32.8	38.0	38.9	39.8	40.7	41.5
Total Carbon Stocks	173.5	235.6	251.6	255.0	258.4	261.5	264.7

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. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-57. Total yard trimmings and food scraps CO₂ flux in 2014 was estimated to be between -18.0 and -4.5 MMT CO₂ Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of

44 percent below to 64 percent above the 2014 flux estimate of -11.6 MMT CO₂ Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

Table 6-57: Approach 2 Quantitative Uncertainty Estimates for CO₂ Flux from Yard Trimmings and Food Scraps (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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	(11.6)	(18.0)	(4.5)	-44%	+64%

^a Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. The QA/QC analysis did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The current Inventory has been revised relative to the previous report. Generation and recovery data for yard trimmings and food scraps was not previously provided for every year from 1960 in the *Advancing Sustainable Materials Management: Facts and Figures 2013* report. EPA has since released historical data, which included data for each year from 1960 through 2013. The recalculations based on these historical data resulted in changes ranging from a one percent increase in sequestration in 2001 to a 7 percent decrease in sequestration in 2013, and an average 0.66 percent decrease in sequestration across the 1990 through 2013 time series compared to the 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 CH₄ emissions described in the Waste chapter. For example, the Waste chapter does not distinguish landfill CH₄ emissions from yard trimmings and food scraps separately from landfill CH₄ emissions from total bulk (i.e., municipal solid) waste, which includes yard trimmings and food scraps.

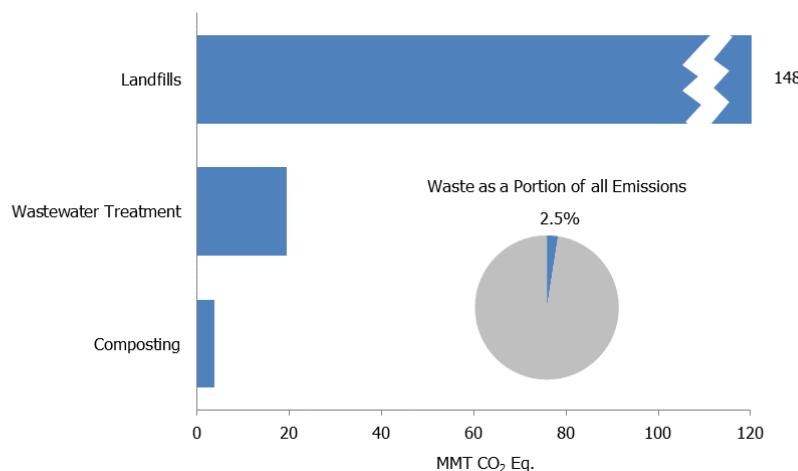
In addition, additional data will be evaluated from recent peer-reviewed literature that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values. Whether to update the weighted national average component-specific decay rate using new U.S. Census data, if any are available, will also be investigated.

The yard waste composition will also be evaluated to determine if changes need to be made based on changes in residential practices, research 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.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1). Landfills accounted for approximately 20.2 percent of total U.S. anthropogenic methane (CH_4) emissions in 2014, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 2.0 percent and less than one 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 1.7 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: 2014 Waste Chapter Greenhouse Gas Sources (MMT CO_2 Eq.)



Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Sinks

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 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 2006).¹ Additionally, the calculated emissions and sinks 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.² The use of consistent methods to calculate emissions and sinks by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. In this regard,

¹ See <<http://www.ipcc-nggip.iges.or.jp/public/index.html>>.

² See <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2>>.

U.S. emissions and sinks reported in this Inventory report are comparable to emissions and sinks reported by other countries. The manner that emissions and sinks are provided in this Inventory is one of many ways U.S. emissions and sinks could be examined; this Inventory report presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC. Emissions and sinks provided in the current Inventory do not preclude alternative examinations, but rather presents emissions and sinks in a common format consistent with how countries are to report inventories under the UNFCCC.³ The report itself, and this chapter, follows this standardized format, and provides an explanation of the IPCC methods used to calculate emissions and sinks, and the manner in which those calculations are conducted. The UNFCCC incorporated the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* as the standard for Annex I countries at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). This chapter presents emission estimates calculated in accordance with the methodological guidance provided in these guidelines.

Overall, in 2014, waste activities generated emissions of 171.4 MMT CO₂ Eq., or 2.5 percent of total U.S. greenhouse gas emissions.

Table 7-1: Emissions from Waste (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	195.6	171.8	159.4	161.5	159.2	161.1	164.7
Landfills	179.6	154.0	142.1	144.4	142.3	144.3	148.0
Wastewater Treatment	15.7	15.9	15.5	15.3	15.0	14.8	14.7
Composting	0.4	1.9	1.8	1.9	1.9	2.0	2.1
N₂O	3.7	6.0	6.1	6.4	6.5	6.6	6.7
Wastewater Treatment	3.4	4.3	4.5	4.7	4.8	4.8	4.8
Composting	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Total	199.3	177.8	165.5	167.8	165.7	167.8	171.4

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
CH₄	7,823	6,871	6,377	6,459	6,369	6,445	6,589
Landfills	7,182	6,161	5,685	5,774	5,691	5,772	5,919
Wastewater Treatment	626	636	618	610	601	592	588
Composting	15	75	73	75	77	81	82
N₂O	12	20	21	21	22	22	22
Wastewater Treatment	11	15	15	16	16	16	16
Composting	1	6	5	6	6	6	6

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO₂), CH₄, and N₂O 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 2014 resulted in 9.7 MMT CO₂ 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 7.4.

³ For example, see <<http://www.epa.gov/ghgreporting/ghgrp-methodology-and-verification>>.

Box 7-2: Waste Data from the Greenhouse Gas Reporting Program

On October 30, 2009, the U.S. EPA published a rule for the mandatory reporting of greenhouse gases from large greenhouse gas emissions sources in the United States. Implementation of 40 CFR Part 98 is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP). 40 CFR Part 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO₂ underground for sequestration or other reasons and requires reporting by 41 industrial categories. 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 CO₂ Eq. per year.

EPA's GHGRP dataset and the data presented in this Inventory report are complementary and, as indicated in the respective planned improvements sections for source categories in this chapter, EPA is analyzing how to use facility-level GHGRP data to improve the national estimates presented in this Inventory. 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. This may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. It should be noted that the definitions for source categories in EPA's GHGRP may differ from those used in this 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 source categories identified in the *2006 IPCC Guidelines* (IPCC 2006). Further information on the reporting categorizations in EPA's GHGRP and specific data caveats associated with monitoring methods in EPA's GHGRP has been provided on the EPA's GHGRP website.⁴

EPA presents the data collected by EPA's GHGRP through a data publication tool that allows data to be viewed in several formats including maps, tables, charts and graphs for individual facilities or groups of facilities.⁵

7.1 Landfills (IPCC 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 commonly 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 7-1. 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 7-3. 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 accept waste produced by industrial activity, such as factories, mills, and mines.

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 (CH₄) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO₂) and 50 percent CH₄, by volume. Landfill biogas also

⁴ See

<<http://www.ccdsupport.com/confluence/display/ghgp/Detailed+Description+of+Data+for+Certain+Sources+and+Processes>>.

⁵ See <<http://ghgdata.epa.gov>>.

contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition by-products or volatilization of biodegradable wastes (EPA 2008).

Methane and CO₂ are the primary constituents of landfill gas generation and emissions. However, the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines* set an international convention to not report biogenic CO₂ released due to landfill decomposition in the Waste sector (IPCC 2006). Carbon dioxide emissions from landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Box 7-4). Additionally, emissions of NMOC and VOC are not estimated because they are considered to be emitted in trace amounts. Nitrous oxide (N₂O) 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 N₂O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N₂O emissions from solid waste disposal sites “because they are not significant.” Therefore, only CH₄ 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 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., composition of waste-in-place, size, climate, cover material); (3) the amount of CH₄ that is recovered and either flared or used for energy purposes; and (4) the amount of CH₄ oxidized as the landfill gas passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills practice 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 commonly 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 2014, landfill CH₄ emissions were approximately 148.0 MMT CO₂ Eq. (5,919 kt), representing the third largest source of CH₄ emissions in the United States, behind natural gas systems and enteric fermentation. Emissions from MSW landfills accounted for approximately 95 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,900 to 2,000 operational MSW landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH₄ emitted (EPA 2015b; EPA 2015c). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure date is known, [EPA 2015b; WBJ 2010]). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to approximately 2,000 in the 2010s, the average landfill size has increased (EPA 2015c; BioCycle 2010; WBJ 2010). The exact number of active and closed dedicated industrial waste landfills is not known at this time, but the Waste Business Journal total for landfills accepting industrial and construction and demolition debris for 2010 is 1,305 (WBJ 2010). Only 176 facilities with industrial waste landfills reported under Subpart TT (Industrial Waste Landfills) of EPA’s Greenhouse Gas Reporting Program (GHGRP) since reporting began in 2011, indicating that there may be several hundreds of industrial waste landfills that are not required to report under EPA’s GHGRP, or that the actual number of industrial waste landfills in the United States is relatively low compared to MSW landfills.

The estimated annual quantity of waste placed in MSW landfills increased 39 percent from approximately 205 MMT in 1990 to 226 MMT in 2000 and then decreased by 11 percent to 262 MMT in 2014 (see Annex 3.14). The annual amount of waste 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 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. 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 11.3 MMT in 2014.

Net CH₄ emissions have decreased since 1990, and have fluctuated around 6 MMT over the past few years (see Table 7-4). This slowly decreasing trend since the 1990’s can be mostly attributed to an approximately 21 percent reduction in the amount of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series (EPA 2015c) and an increase in the amount of landfill gas collected

and combusted (i.e., used for energy or flared) at MSW landfills, resulting in lower net CH₄ emissions from MSW landfills. For instance, in 1990, approximately 0.7 MMT of CH₄ were recovered and combusted from landfills, while in 2014, approximately 7.5 MMT of CH₄ were recovered and combusted, representing an average annual increase in the quantity of CH₄ recovered and combusted at MSW landfills from 1990 to 2014 of 11 percent (see Annex 3.14). Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

The quantity of recovered CH₄ that is either flared or used for energy purposes at MSW landfills has continually increased as a result of 1996 federal regulations that require large MSW landfills to collect and combust landfill gas (see 40 CFR Part 60, Subpart Cc 2005 and 40 CFR Part 60, Subpart WWW 2005). Voluntary programs that encourage CH₄ recovery and beneficial reuse, such as EPA's Landfill Methane Outreach Program (LMOP) and federal and state incentives that promote renewable energy (e.g., tax credits, low interest loans, and Renewable Portfolio Standards), have also contributed to increased interest in landfill gas collection and control. In 2014, an estimated 10 new landfill gas-to-energy (LFGTE) projects (EPA 2015a; EPA 2015b) and 3 new flares began operation. While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase in collection and combustion no longer exceeds the rate of additional CH₄ generation from the amount of organic MSW landfilled as the U.S. population grows.

Table 7-3: CH₄ Emissions from Landfills (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
MSW Landfills	205.3	287.0	321.0	325.2	328.6	332.0	335.4
Industrial Landfills	12.1	15.9	16.4	16.4	16.5	16.5	16.6
Recovered	(17.9)	(131.8)	(179.5)	(181.2)	(187.0)	(188.2)	(187.7)
Oxidized ^a	(20.0)	(17.1)	(15.8)	(16.0)	(15.8)	(16.0)	(16.4)
Total	179.6	154.0	142.1	144.4	142.3	144.3	148.0

^a Includes oxidation at municipal and industrial landfills.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 7-4: CH₄ Emissions from Landfills (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
MSW Landfills	8,214	11,482	12,839	13,008	13,144	13,280	13,418
Industrial Landfills	484	636	656	657	659	661	665
Recovered	(718)	(5,272)	(7,178)	(7,249)	(7,480)	(7,529)	(7,507)
Oxidized ^a	(798)	(685)	(632)	(642)	(632)	(641)	(658)
Total	7,182	6,161	5,685	5,774	5,691	5,772	5,919

^a Includes oxidation at municipal and industrial landfills.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology

Methane emissions from landfills were estimated as the CH₄ produced from MSW landfills, plus the CH₄ produced by industrial waste landfills, minus the CH₄ recovered and combusted from MSW landfills, minus the CH₄ oxidized before being released into the atmosphere:

$$\text{CH}_4, \text{Solid Waste} = [\text{CH}_4, \text{MSW} + \text{CH}_4, \text{Ind} - R] - \text{Ox}$$

where,

CH ₄ ,Solid Waste	= CH ₄ emissions from solid waste
CH ₄ ,MSW	= CH ₄ generation from MSW landfills
CH ₄ ,Ind	= CH ₄ generation from industrial landfills
R	= CH ₄ recovered and combusted (only for MSW landfills)
Ox	= CH ₄ oxidized from MSW and industrial waste landfills before release to the atmosphere

The methodology for estimating CH₄ emissions from landfills is based on the first order decay (FOD) model described by the *2006 IPCC Guidelines*. Methane generation is based on nationwide MSW generation data, to

which a national average disposal factor is applied; it is not landfill-specific. The amount of CH₄ recovered, however, is landfill-specific, but only for MSW landfills due to a lack of data specific to industrial waste landfills. Values for the CH₄ generation potential (L_0) and the decay rate constant (k) used in the first order decay model were obtained from an analysis of CH₄ recovery rates for a database of 52 landfills and from published studies of other landfills (RTI 2004; EPA 1998; SWANA 1998; Peer, Thorneloe, and Epperson 1993). The decay rate constant was found to increase with average annual rainfall; consequently, values of k were developed for three ranges of rainfall, or climate types (wet, arid, and temperate). The annual quantity of waste placed in landfills was apportioned to the three ranges of rainfall based on the percent of the U.S. population in each of the three ranges. Historical census data were used to account for the shift in population to more arid areas over time (U.S. Census Bureau 2015). An overview of the data sources and methodology used to calculate CH₄ generation and recovery is provided below, while a more detailed description of the methodology used to estimate CH₄ emissions from landfills can be found in Annex 3.14.

States and local municipalities across the United States do not consistently track and report quantities of MSW generated or collected for management, nor are end-of-life disposal methods reported to a centralized system. Therefore, national MSW landfill waste generation and disposal data are obtained from secondary data, specifically the State of Garbage (SOG) surveys, published approximately every two years, with the most recent publication date of 2014. The SOG survey is the only continually updated nationwide survey of waste disposed in landfills in the United States and is the primary data source with which to estimate nationwide CH₄ generation from MSW landfills. The SOG surveys use the principles of mass balance where all MSW generated is equal to the amount of MSW landfilled, combusted in waste-to-energy plants, composted, and/or recycled (BioCycle 2010; Shin 2014). This approach assumes that all waste management methods are tracked and reported to state agencies. Survey respondents are asked to provide a breakdown of MSW generated and managed by landfilling, recycling, composting, and combustion (in waste-to-energy facilities) in actual tonnages as opposed to reporting a percent generated under each waste disposal option. The data reported through the survey have typically been adjusted to exclude non-MSW materials (e.g., industrial and agricultural wastes, construction and demolition debris, automobile scrap, and sludge from wastewater treatment plants) that may be included in survey responses. In the most recent survey, state agencies were asked to provide already filtered, MSW-only data. Where this was not possible, they were asked to provide comments to better understand the data being reported. All state disposal data are adjusted for imports and exports across state lines where imported waste is included in a particular state's total while exported waste is not. Methodological changes have occurred over the time frame the SOG survey has been published, and this has affected the fluctuating trends observed in the data (RTI 2013).

The SOG survey is voluntary and not all states provide data for each survey year. Where no waste generation data are provided by a state in the SOG survey, the amount generated is estimated by multiplying the waste per capita from a previous SOG survey by that particular state's population. If that particular state did not report any waste generation data in the previous SOG survey, the average nationwide waste per capita rate for the current SOG survey is multiplied by that particular state's population. The quantities of waste generated across all states are summed and that value is then used as the nationwide quantity of waste generated in a given reporting year. Additionally, because the SOG survey does not account for waste generated in U.S. Territories, waste generation for the territories was estimated using population data obtained from the U.S. Census Bureau (2014) and national per capita solid waste generation from the SOG survey (Shin 2014).

State-specific landfill waste generation data and a national average disposal factor for 1989 through 2008 were obtained from the SOG survey every two years (i.e., 2002, 2004, 2006, and 2008 as published in BioCycle 2006, and 2008 as published in BioCycle 2010). The most recent SOG survey provides data for 2011 (Shin 2014). State-specific landfill waste generation data for the years in-between the SOG surveys (e.g., 2001, 2003, 2005, 2007, 2009, 2010, 2012, 2013, and 2014) were either interpolated or extrapolated based on the SOG data and the U.S. Census population data. Because the most recent SOG survey was published in 2014 for the 2011 year, the annual quantities of waste generated for the years 2012 to 2014 were extrapolated based on the 2011 data and population growth. Waste generation data for 2012 through 2014 will be updated as new SOG surveys are published.

Estimates of the quantity of waste landfilled from 1989 to 2014 are determined by applying an average national waste disposal factor to the total amount of waste generated (i.e., the SOG data). A waste disposal factor is determined for each year an SOG survey is published and equals the ratio of the total amount of waste landfilled in the United States to the total amount of waste generated in the United States. The waste disposal factor is interpolated or extrapolated for the years in-between the SOG surveys, as is done for the amount of waste generated for a given survey year.

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 CH₄ generation, estimates for those years were included in the FOD model for completeness in accounting for CH₄ generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in the current Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (Methane Conversion Factor, MCF, of 1) and those disposed in dumps (MCF of 0.6). All calculations after 1980 assume waste is disposed in managed, modern landfills. See Annex 3.14 for more details.

Methane recovery is currently only accounted for at MSW landfills. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only two of the 176 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2015b). 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 estimated landfill gas recovered per year (R) at MSW landfills was based on a combination of four databases and including recovery from flares and/or landfill gas-to-energy projects:

- EPA's GHGRP dataset for MSW landfills (EPA 2015b);
- A database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007);
- A database of LFGTE projects that is primarily based on information compiled by the EPA LMOP (EPA 2015a); and
- The flare vendor database (contains updated sales data collected from vendors of flaring equipment).

The same landfill may be included one or more times across these four databases. To avoid double- or triple-counting CH₄ recovery, the landfills across each database were compared and duplicates identified. A hierarchy of recovery data is used based on the certainty of the data in each database. In summary, the GHGRP > EIA > LFGTE > flare vendor database. The rationale for this hierarchy is described below.

EPA's GHGRP MSW landfills database was first introduced as a data source for the 1990 to 2013 Inventory. EPA's GHGRP MSW landfills database contains facility-reported data that undergoes rigorous verification, thus it is considered to contain the least uncertain data of the four databases. However, as mentioned earlier, this database is unique in that it only contains a portion of the landfills in the United States (although, presumably the highest emitters since only those landfills that meet a certain CH₄ generation threshold must report) and only contains data for 2010 and later. Directly reported values for CH₄ recovery to the GHGRP database were used for years 2010 through 2014. Methane recovery prior to 2010 has been estimated using an Excel forecasting function so that the GHGRP data source can be applied to the entire time series (1990 to 2014) instead of 2010 to 2014 only. If a landfill in EPA's GHGRP was also in the LFGTE or EIA databases, the landfill gas project information, specifically the project start year, from either the LFGTE or EIA databases was used as the cutoff year for the estimated CH₄ recovery in the GHGRP database. For example, if a landfill reporting under EPA's GHGRP was also included in the LFGTE database under a project that started in 2002 that is still operational, the CH₄ recovery in the GHGRP database was back-calculated to the year 2002 only. This method, although somewhat uncertain, can be refined in future Inventory years after further investigating the landfill gas project start years for landfills in the GHGRP database.

If a landfill in the GHGRP MSW landfills database was also in the EIA, LFGTE, and/or flare vendor database, the avoided emissions were only based on EPA's GHGRP MSW landfills database to avoid double or triple counting the recovery amounts. In other words, the recovery from the same landfill was not included in the total recovery from the EIA, LFGTE, or flare vendor databases.

If a landfill in the EIA database was also in the LFGTE and/or the flare vendor database, the CH₄ recovery was based on the EIA data because landfill owners or operators directly reported the amount of CH₄ recovered using gas flow concentration and measurements, and because the reporting accounted for changes over time. However, as the EIA database only includes facility-reported data through 2006, the amount of CH₄ recovered for years 2007 and later were assumed to be the same as in 2006 for landfills that are in the EIA database, but not in the GHGRP or LFGTE databases. This quantity likely underestimates flaring because the EIA database does not have information

on all flares in operation for the years after 2006. However, nearly all (93 percent) of landfills in the EIA database also report to the GHGRP, which means that only seven percent of landfills in the EIA database are counted in the total recovery.

If both the flare data and LFGTE recovery data were available for any of the remaining landfills (i.e., not in the EIA or GHGRP databases), then the avoided emissions were based on the LFGTE data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The LFGTE database is based on the most recent EPA LMOP database (published annually). The remaining portion of avoided emissions is calculated by the flare vendor database, which estimates CH₄ combusted by flares using the midpoint of a flare's reported capacity. New flare vendor sales data were unable to be obtained for the current Inventory year. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LFGTE database was avoided by subtracting emission reductions associated with LFGTE projects for which a flare had not been identified from the emission reductions associated with flares (referred to as the flare correction factor). A further explanation of the methodology used to estimate the landfill gas recovered can be found in Annex 3.14.

The destruction efficiencies reported through EPA's GHGRP were applied to the landfills in the GHGRP MSW landfills database. The median value of the reported destruction efficiencies was 99 percent for all reporting years (2010 through 2014). A destruction efficiency of 99 percent was applied to CH₄ recovered to estimate CH₄ emissions avoided due to the combusting of CH₄ in destruction devices (i.e., flares) in the EIA, LFGTE, and flare vendor databases. The 99 percent destruction efficiency value selected was based on the range of efficiencies (86 to greater than 99 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors*, Draft Section 2.4, Table 2.4-3 (EPA 2008). A typical value of 97.7 percent was presented for the non-CH₄ components (i.e., volatile organic compounds and non-methane organic compounds) in test results (EPA 2008). An arithmetic average of 98.3 percent and a median value of 99 percent are derived from the test results presented in EPA (2008). Thus, a value of 99 percent for the destruction efficiency of flares has been used in the Inventory methodology. Other data sources supporting a 99 percent destruction efficiency include those used to establish New Source Performance Standards (NSPS) for landfills and in recommendations for shutdown flares used by the EPA LMOP.

Emissions from industrial waste landfills were estimated from industrial production data from 2013 extrapolated to 2014 (ERG 2014), waste disposal factors, and the FOD model. The Inventory methodology assumes over 99 percent of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors (EPA 1993), thus estimates of industrial landfill emissions focused on these two sectors. There are currently no 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 and supports the focus of the Inventory on the two selected sectors, but is not comprehensive. Therefore, 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. 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 CH₄ oxidized by the landfill cover at both municipal and industrial waste landfills was assumed to be 10 percent of the CH₄ generated that is not recovered (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996). To calculate net CH₄ emissions, both CH₄ recovered and CH₄ oxidized were subtracted from CH₄ generated at municipal and industrial waste landfills.

Uncertainty and Time-Series Consistency

Several types of uncertainty are associated with the estimates of CH₄ emissions from MSW and industrial waste landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH₄ production: the amount and composition of waste placed in every MSW and industrial waste landfill for each year of a landfill's operation. The *SOG survey* is the only nationwide data source that compiles the amount of MSW disposed at the state-level. The surveys do not include information on waste composition and there are no comprehensive data sets that compile quantities of waste disposed or waste composition by landfill. EPA's GHGRP allows facilities to report annual quantities of waste disposed by composition, but most MSW landfills report annual waste disposed as bulk MSW versus the detailed waste

composition data. Some MSW landfills have conducted detailed waste composition studies, but the data are scarce over the time series and across the country. EPA is currently compiling the waste composition studies and data that have been performed in the past decade and may revise the default waste composition applied to MSW landfilled in the FOD model in future Inventory estimates.

The approach used in the solid waste emission estimates assumes that the CH₄ generation potential (L_o) and the rate of decay that produces CH₄ from MSW, as determined from several studies of CH₄ 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 Inventory methodology is not facility-specific modeling and while this approach may over- or under-estimate CH₄ generation at some landfills if used at the facility-level, the end result is expected to balance out because it is being applied nationwide. There is also a high degree of uncertainty and variability associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006).

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary uncertainty with respect to the industrial waste generation and emissions estimates. The approach used here assumes that the majority (99 percent) of industrial waste disposed of in industrial waste landfills 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 of waste generated 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.

Aside from the uncertainty in estimating landfill CH₄ generation, uncertainty also exists in the estimates of the landfill gas oxidized. A constant oxidation factor of 10 percent as recommended by the IPCC for managed landfills is used for both MSW and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system. The number of published field studies measuring the rate of oxidation has increased substantially since the *2006 IPCC Guidelines* were published and, as discussed in the Potential Improvements section, efforts are being made to review the literature and revise this value based on recent, peer-reviewed studies.

Another significant source of uncertainty lies with the estimates of CH₄ recovered by flaring and gas-to-energy projects at MSW landfills. The GHGRP MSW landfills database was added as a fourth recovery database in the 1990 through 2013 Inventory report. 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; in reality, the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH₄ recovered.

The LFGTE database is updated annually. The flare database is populated by the voluntary sharing of flare sales data by select vendors and is not able to be obtained annually, which likely underestimates 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 CH₄ recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data are given precedence because CH₄ recovery is directly reported by landfills and undergoes a rigorous verification process; the EIA data are given second priority because facility data were directly reported; the LFGTE data are given third priority because CH₄ recovery is estimated from facility-reported LFGTE system characteristics; and the flare data are given fourth 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 CH₄ gas recovery; however, the number of unique landfills between the four databases does differ.

The IPCC 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 CH₄ estimated to be recovered). This 10 percent uncertainty factor applies to the LFGTE 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 model and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5. Industrial waste landfills are shown with a lower range of uncertainty due to the smaller number of data sources and associated uncertainty involved. For example, three data sources are used to generate the annual quantities of MSW waste disposed over the 1940 to current year timeframe, while industrial waste landfills rely on two data sources.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. In 2014, landfill CH₄ emissions were estimated to be between 86.4 and 230.0 MMT CO₂ Eq., which corresponds to a range of 38 percent below to 64 percent above the 2014 emission estimate of 148.0 MMT CO₂ Eq.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Landfills (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)		Uncertainty Range Relative to Emission Estimate ^a (%)			
		Lower Bound	Upper Bound	Lower Bound	Upper Bound		
Landfills	CH ₄	148.0	86.4	230.0	-38%	+64%	
MSW	CH ₄	133.0	72.5	216.7	-42%	+73%	
Industrial	CH ₄	15.0	10.4	18.7	-30%	+25%	

^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 2014. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A Quality Assurance/Quality Control analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are performed for the transcription of the published data set used to populate the Inventory data set, including the published GHGRP and LFGTE databases, but are not performed on the data itself against primary data used. A primary focus of the QA/QC checks was to ensure that CH₄ recovery estimates were not double-counted and that all LFGTE projects and flares were included in the respective project databases. Both manual and electronic checks were used to ensure that emission avoidance from each landfill was calculated only once. The primary calculation spreadsheet is tailored from the IPCC waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values were verified by secondary QA/QC review.

Recalculations Discussion

Four major methodological recalculations were performed for the current Inventory.

First, a rigorous review of the flare and LFGTE projects across the four recovery databases was conducted. Extensive corrections were made to avoid double counting of projects across the recovery databases. The largest change compared to the previous Inventory was in the LFGTE database where an additional 382 projects were matched to facilities reporting under the GHGRP (note that a landfill may have multiple projects and new facilities have reported under the GHGRP for the first time since the initial landfill matching exercise in 2012). This additional matching results in a decrease in total recovery compared to the previous Inventory by approximately 1 MMT. The second largest change compared to the previous Inventory was in the flare database where 79 flare projects were matched to facilities reporting under the GHGRP or included in the LFGTE database. These projects, which were double-counted in previous Inventories, account for approximately 0.44 MMT of avoided emissions. Oftentimes, the name of a landfill and/or address differs between the databases and additional Internet searching allows for the landfills to be matched. Additionally, several facilities in the LFGTE database were removed because

they were not in the published LMOP database for the current or past two years (EPA 2015a). The LFGTE is an enhanced version of the LMOP database and if a landfill is no longer in the LMOP database, the Inventory assumes it was added erroneously. These revisions resulted in larger than expected changes to the annual quantities of the annual CH₄ recovery estimates used in the net CH₄ emissions compared to the previous Inventory, and, in turn, an increase in net CH₄ emissions across the time series.

Second, the GHGRP CH₄ recovery data were back-calculated for landfills in the GHGRP database for years prior to the first GHGRP reporting year (typically 2010 for most landfills). In the previous Inventory, there was a significant change in the total recovery between years 2009 and 2010. This methodological change was made to smooth the recovery data for years prior to 2009. An Excel forecast function was used to back-calculate recovery to an assumed project start year based on four years of reported recovery data for each landfills and project information contained in the LFGTE and EIA databases.

Third, the flare correction factor was revised. This effort included reviewing the 27 flare projects included in the flare correction factor to identify them with landfills in the GHGRP, LFGTE, or EIA databases, or match them to existing operational or closed landfills through and Internet search (RTI 2015a). The number of flares included in the flare correction factor decreased from 27 to 19. The impact on CH₄ recovery varies by year and is a modest amount.

Fourth, the DOC value for landfilled pulp and paper waste was revised from 0.20 to 0.15 based a literature review of pulp and paper waste characterization studies (RTI 2015b) and data reported under the GHGRP. A representative DOC value is likely to be within the range of 0.15 to 0.16 as calculated using the facility-specific DOC values reported under Subpart TT and data presented in Heath et al. (2010). However, a lower DOC value of 0.10 was calculated when considering only the 21 out of 76 pulp and paper facilities that provided waste-stream-specific DOC values in their 2013 annual reports. Further refined data may be available in future GHGRP reporting years as additional facilities choose to perform waste stream-specific analyses. Revising the DOC value for pulp and paper waste to 0.15 at this time is a conservative approach. This value will be re-assessed in future Inventory years as more information becomes available.

The overall impact to the Inventory from these changes resulted in an average increase of nearly 14 percent across the time series. A significant increase in net CH₄ emissions for the years 2010 through 2013 ranging from 20 to 52 percent higher in the current Inventory compared to the 1990 to 2013 Inventory.

Planned Improvements

Improvements being examined for future Inventory estimates include: (1) investigating alternative data sources for nationwide MSW disposal; (2) incorporating additional data from recent peer-reviewed literature to modify the default oxidation factor applied to MSW and industrial waste landfills (currently 10 percent); (3) either modifying the bulk MSW DOC value or estimating emissions using a waste-specific approach in the FOD model using data from the GHGRP and peer-reviewed literature; (4) reviewing waste-stream specific DOC and decay rate constant (k) value data reported for industrial waste landfills (specifically pulp and paper waste) as reported under EPA's GHGRP; and (5) increasing communications with flare vendors to obtain methane recovery data for landfills not reporting to EPA's GHGRP or providing information to LMOP.

The EPA has relied on a top-down approach to calculate CH₄ generation for MSW landfills. The *SOG* survey has been used in the current and previous Inventories, but is not anticipated to be published as routinely as it has been in the past. EPA is investigating whether a bottom-up approach can be used in future Inventories by supplementing the GHGRP annual waste disposal data with other relevant datasets (e.g., LMOP, state data) to provide the annual waste disposal data needed for the FOD model. EPA's GHGRP requires landfills meeting or exceeding a threshold of 25,000 metric tons of CH₄ generation per year to report a variety of facility-specific information, including historical and current waste disposal quantities by year, CH₄ generation, gas collection system details, CH₄ recovery, and CH₄ emissions. The landfills reporting to the GHGRP are considered the largest emitters, but not all landfills are required to report. However, when this dataset is supplemented with others, such as the EPA LMOP data (incorporated into the Inventory through the LFGTE database), or the Waste Business Journal data, a complete data set of the annual quantity of waste landfilled may be represented.

In the draft for the 1990 through 2014 Inventory released for its public comment period, the EPA incorporated year-to-year, facility-level waste disposal quantities as reported to EPA's GHGRP, supplemented with data from LMOP.

The FOD model was then applied using a bulk waste DOC value of 0.20, as has been utilized as the best methodological approach for previous Inventory emission estimates. This recalculation resulted in a large increase in estimated CH₄ emissions from landfills over the time series of the Inventory. During the public comment period on the draft Inventory, the EPA received comments from the waste industry that, while the 0.20 DOC is appropriate for MSW bulk waste, there is a substantial amount of inert waste disposed in addition to that MSW bulk waste which should instead be assigned a DOC value of zero because it does not contribute to CH₄ generation. According to these waste industry comments, the addition of inerts is a trend that has been occurring for many years at MSW landfills. Despite the use of the same FOD methodology and same assumptions on DOC for estimating emissions from MSW landfills, the EPA had not received this information from the waste industry during previous public comment periods on prior draft Inventory reports. The EPA has determined that further review of the waste disposal quantities and DOC values reported to EPA's GHGRP using the approved reporting requirements is necessary in light of the waste industry comments on the draft Inventory. As such, the recalculation presented in the draft Inventory using the GHGRP waste disposal data was not incorporated for the final Inventory report. The integration of the GHGRP data will be explored further with additional waste industry stakeholder input so that it may be used, and so that recalculated emission estimates can be provided in the 1990 through 2015 Inventory.

A standard CH₄ oxidation factor of 10 percent has been used for both industrial and MSW landfills in prior Inventory reports and is currently recommended as the default for well-managed landfills in the latest *IPCC Guidelines* (2006). Recent comments on the Inventory methodology indicated that a default oxidation factor of 10 percent may be less than oxidation rates achieved at well-managed landfills with gas collection and control. As a first step toward revising this oxidation factor, a literature review was conducted in 2011 (RTI 2011). In addition, facilities reporting under EPA's GHGRP have the option to use an oxidation factor other than 10 percent (e.g., 0, 25, or 35 percent) if the calculated result of CH₄ flux calculations warrants it. Various options are being investigated to incorporate this facility-specific data for landfills reporting under EPA's GHGRP and/or the remaining facilities.

The standard oxidation factor (10 percent) is applied to the total amount of waste generated nationwide. Changing the oxidation factor and calculating the amount of CH₄ oxidized from landfills with gas collection and control requires the estimation of waste disposed in these types of landfills over the entire time series. Although EPA's GHGRP does not capture every landfill in the United States, larger landfills are expected to meet the reporting thresholds and are reporting waste disposal information by year. At this time, data are available to calculate the amount of waste disposed of at landfills with and without gas collection systems in the United States for landfills reporting under EPA's GHGRP. After investigating the landfills not reporting under EPA's GHGRP to determine the presence of a landfill gas collection and control system and waste disposal data, a modification to the Inventory waste model to apply different oxidation factors depending on the presence of a gas collection system may be possible.

Other potential improvements to the methodology may be made in the future using other portions of the GHGRP dataset, specifically for inputs to the FOD equation. The approach used in the Inventory to estimate CH₄ generation assumes a bulk waste-specific DOC value that may not accurately capture the changing waste composition over the time series (e.g., the reduction of organics entering the landfill environment due to increased composting, see Box 7-2). Using data obtained from EPA's GHGRP and any publicly available landfill-specific waste characterization studies in the United States, the methodology may be modified to incorporate a waste composition approach, or revisions may be made to the bulk waste DOC value currently used. Additionally, GHGRP data could be analyzed and a weighted average for the CH₄ correction factor (MCF), fraction of CH₄ (F) in the landfill gas, the destruction efficiency of flares, and the decay rate constant (k) could replace the values currently used in the Inventory. At this time, the majority of landfills reporting under EPA's GHGRP select bulk MSW for their waste composition.

In addition to MSW landfills, industrial waste landfills at facilities emitting CH₄ in amounts equivalent to 25,000 metric tons or more of CO₂ Eq. were required to report their GHG emissions beginning in September 2012 through EPA's GHGRP. Similar data for industrial waste landfills as is required for the MSW landfills are being reported. Any additions or improvements to the Inventory using reported GHGRP data will be made for the industrial waste landfill source category. As mentioned in the recalculation discussion, the DOC value for pulp and paper waste will be reviewed against new GHGRP data to determine if further revisions to the DOC value of 0.15 are necessary. Another potential improvement includes a revision to the waste disposal factor currently used by the Inventory for the pulp and paper sector using production data from pulp and paper facilities that reported annual production and annual disposal data under EPA's GHGRP. The addition of industrial sectors other than pulp and paper and food processing (e.g., metal foundries, petroleum refineries, and chemical manufacturing facilities) to the Inventory may also be investigated.

Lastly, voluntary flare sales data was not able to be obtained from vendors who have previously provided this data. The impacts on the Inventory are minimal considering the coverage of EPA's GHGRP and LMOP, but is necessary to provide a representative picture of the extent of CH₄ recovery in the United States.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste generated in the United States can be managed through landfilling, recycling, composting, and combustion with energy recovery. There are two main sources for nationwide solid waste management data in the United States:

- The *BioCycle* and Earth Engineering Center of Columbia University's State of Garbage (SOG) in America surveys; and
- The EPA's *Municipal Solid Waste in The United States: Facts and Figures* reports.

The SOG surveys collect state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. The survey asks 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 is not available, the survey asks for total tons landfilled. The data are adjusted for imports and exports across state lines so that the principles of mass balance are adhered to, whereby the amount of waste managed does not exceed the amount of waste generated. The SOG reports present survey data aggregated to the state level.

The EPA *Facts and Figures* reports use a materials flow 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, or discarded nationwide. The amount of MSW generated is estimated by adjusting the imports and exports of produced materials to other countries. MSW that is not recycled, composted, or combusted is assumed to be landfilled. The data presented in the report are nationwide totals.

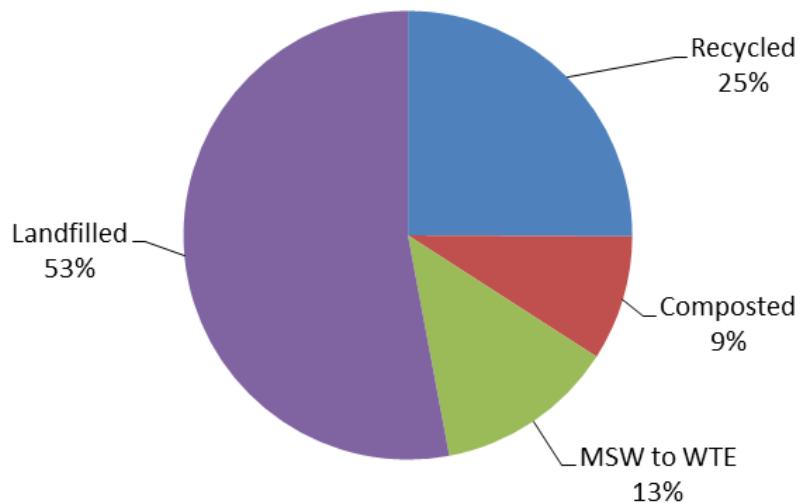
The SOG surveys are the preferred data source for estimating waste generation and disposal amounts in the Inventory because they are considered a more objective, numbers-based analysis of solid waste management in the United States. However, the EPA *Facts and Figures* reports are useful when investigating waste management trends at the nationwide level and for typical waste composition data, which the SOG surveys do not request.

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 chapters 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.

Box 7-4: Overview of the Waste Sector

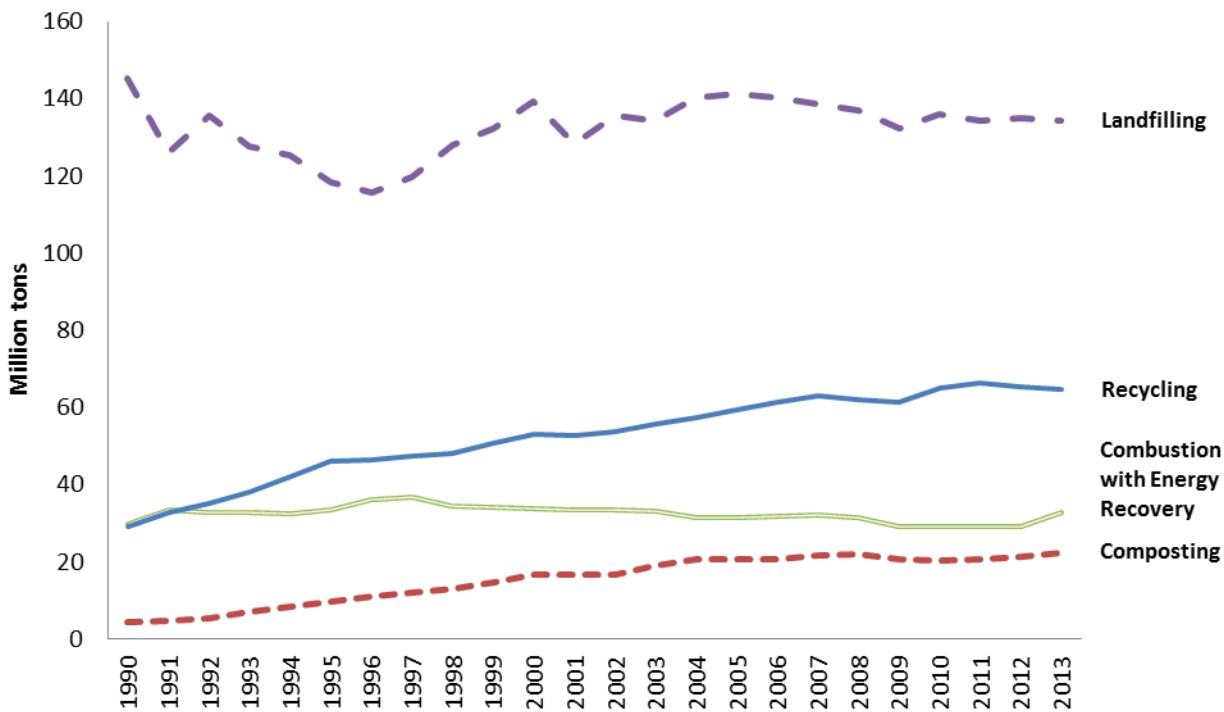
As shown in Figure 7-2 and Figure 7-3, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have normally been disposed of in a landfill.

Figure 7-2: Management of Municipal Solid Waste in the United States, 2013



Source: EPA (2015c).

Figure 7-3: MSW Management Trends from 1990 to 2013



Source: EPA (2015c).

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. Understanding how the waste composition changes over time, specifically for the degradable waste types, is important for estimating greenhouse gas emissions. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste recovery, including recycling and composting (see Table 7-6 and Figure 7-4) do not reflect the impact of backyard composting on yard

trimming generation and recovery estimates. The recovery of food trimmings has been consistently low. Increased recovery of degradable materials reduces the CH₄ generation potential and CH₄ emissions from landfills.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2013 (Percent)

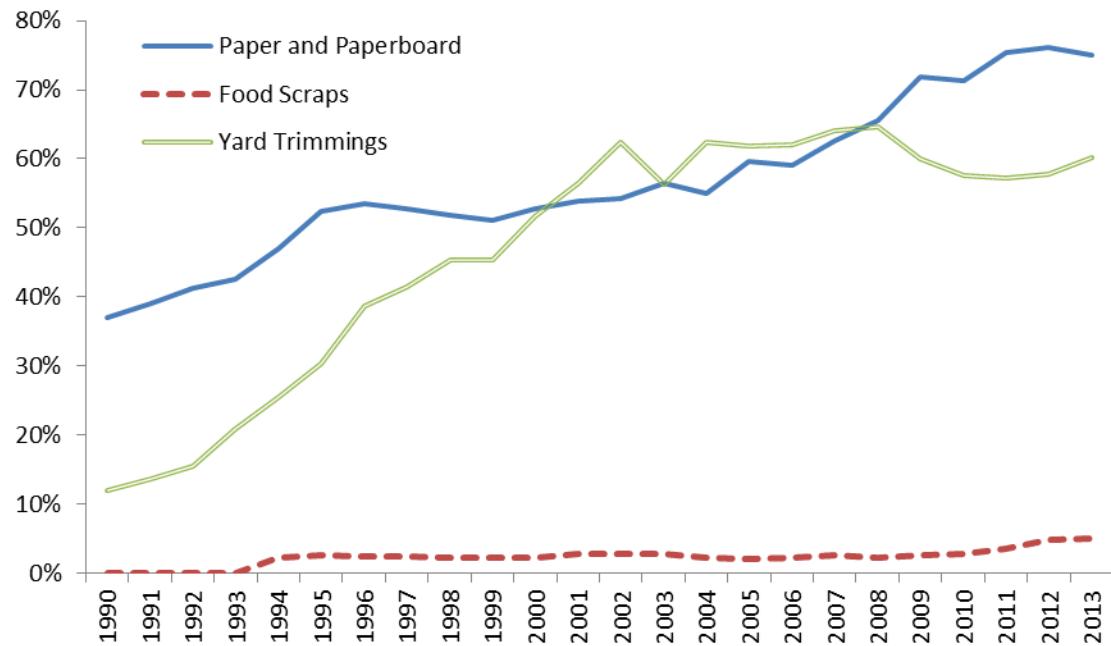
Waste Type	1990	2005	2009	2010	2011	2012	2013
Paper and Paperboard	30.0%	24.5%	14.8%	16.2%	14.8%	14.8%	15.1%
Glass	6.0%	5.7%	5.0%	5.1%	5.1%	5.1%	5.0%
Metals	7.2%	7.7%	8.0%	8.8%	8.9%	9.0%	9.1%
Plastics	9.6%	15.7%	15.8%	17.4%	17.8%	17.6%	17.7%
Rubber and Leather	3.1%	3.5%	3.7%	3.7%	3.8%	3.8%	3.9%
Textiles	2.9%	5.5%	6.3%	6.7%	6.8%	7.4%	7.7%
Wood	6.9%	7.4%	7.7%	8.1%	8.2%	8.2%	8.0%
Other ^a	1.4%	1.8%	1.9%	2.0%	2.0%	2.0%	2.0%
Food Scraps ^b	13.6%	17.9%	19.1%	21.0%	21.4%	21.1%	21.1%
Yard Trimmings ^c	17.6%	7.0%	7.6%	8.6%	8.8%	8.7%	8.1%
Miscellaneous Inorganic Wastes	1.7%	2.1%	2.2%	2.3%	2.4%	2.4%	2.4%

^a Includes electrolytes in batteries and fluff pulp, feces, and urine in disposable diapers. Details may not add to totals due to rounding (EPA 2015c).

^b Data for food scraps were estimated using sampling studies in various parts of the country in combination with demographic data on population, grocery store sales, restaurant sales, number of employees, and number of prisoners, students, and patients in institutions (EPA 2015c).

^c Data for yard trimmings were estimated using sampling studies, population data, and published sources documenting legislation affecting yard trimmings disposal in landfills (EPA 2015c).

Figure 7-4: Percent of Recovered Degradable Materials from 1990 to 2013 (Percent)



Source: EPA 2015c

Box 7-5: Description of a Modern, Managed Landfill

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. 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 exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the New Source Performance Standards (NSPS) 40 CFR Part 60 Subpart WWW. Additionally, state and tribal requirements may exist.⁶

7.2 Wastewater Treatment (IPCC Source Category 5D)

Wastewater treatment processes can produce 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, pathogenic organisms, and chemical contaminants.⁷ Treatment may either occur on site, most commonly through septic systems or package plants, or off site at centralized treatment systems. Centralized wastewater treatment systems may include a variety of processes, ranging from lagooning to advanced tertiary treatment technology for removing nutrients. In the United States, approximately 20 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 2013).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4 . During collection and treatment, wastewater may be accidentally or deliberately managed under anaerobic conditions. In addition, the sludge may be further biodegraded under aerobic or anaerobic conditions. The generation of N_2O may also result from the treatment of domestic wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, ammonia, and proteins. These compounds are converted to nitrate (NO_3^-) through the aerobic process of nitrification. Denitrification occurs under anoxic conditions (without free oxygen), and involves the

⁶ For more information regarding federal MSW landfill regulations, see <http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm>.

⁷ Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

biological conversion of nitrate into dinitrogen gas (N_2). Nitrous oxide can be an intermediate product of both processes, but has typically been associated with denitrification. Recent research suggests that higher emissions of N_2O may in fact originate from nitrification (Ahn et al. 2010). Other more recent research suggests that N_2O may also result from other types of wastewater treatment operations (Chandran 2012).

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). Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production. 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 2014, CH_4 emissions from domestic wastewater treatment were 9.0 MMT CO₂ Eq. (361 kt CH_4). Emissions remained fairly steady from 1990 through 1997, but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004; U.S. Census 2013). In 2014, CH_4 emissions from industrial wastewater treatment were estimated to be 5.7 MMT CO₂ Eq. (227 kt CH_4). Industrial emission sources have generally increased across the time series through 1999 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, and petroleum refining industries. Table 7-7 and Table 7-8 provide CH_4 and N_2O emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O , the United States identifies two distinct sources for N_2O emissions from domestic wastewater: emissions from centralized wastewater treatment processes, and emissions from effluent from centralized treatment systems that has been discharged into aquatic environments. The 2014 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 MMT CO₂ Eq. (1.1 kt N_2O) and 4.5 MMT CO₂ Eq. (15.2 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 4.8 MMT CO₂ Eq. (16.2 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.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO₂ Eq.)

Activity	1990	2005	2010	2011	2012	2013	2014
CH_4	15.7	15.9	15.5	15.3	15.0	14.8	14.7
Domestic	10.5	10.0	9.6	9.4	9.2	9.0	9.0
Industrial ^a	5.1	5.9	5.9	5.9	5.8	5.8	5.7
N_2O	3.4	4.3	4.5	4.7	4.8	4.8	4.8
Domestic	3.4	4.3	4.5	4.7	4.8	4.8	4.8
Total	19.1	20.2	20.0	20.0	19.8	19.6	19.5

^a Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Table 7-8: CH₄ and N₂O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
CH₄	626	636	618	610	601	592	588
Domestic	421	401	384	376	368	361	361
Industrial ^a	205	235	235	234	232	231	227
N₂O	11	15	15	16	16	16	16
Domestic	11	15	15	16	16	16	16

^a Industrial activity includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, and petroleum refining industries.

Note: Totals may not sum due to independent rounding.

Methodology

Domestic Wastewater CH₄ Emission Estimates

Domestic wastewater CH₄ emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH₄ emissions can arise from aerobic systems that are not well managed or that are designed to have periods of anaerobic activity (e.g., constructed wetlands), anaerobic systems (anaerobic lagoons and facultative lagoons), and from anaerobic digesters when the captured biogas is not completely combusted. Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 20 percent) and an emission factor (10.7 g CH₄/capita/day), and then converting the result to kt/year. Methane emissions from POTWs were estimated by multiplying the total BOD₅ produced in the United States by the percent of wastewater treated centrally (about 80 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD₅ treated after primary treatment (67.5 percent), the maximum CH₄-producing capacity of domestic wastewater (0.6), and the relative MCFs for well-managed aerobic (zero), not well managed aerobic (0.3), and anaerobic (0.8) systems with all aerobic systems assumed to be well-managed. Methane emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH₄ in digester biogas (0.65), the density of CH₄ (662 g CH₄/m³ CH₄), and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99). The methodological equations are:

$$\begin{aligned} \text{Emissions from Septic Systems} &= A \\ &= \text{USPOP} \times (\% \text{ onsite}) \times (\text{EF}_\text{SEPTIC}) \times 1/10^9 \times \text{Days} \end{aligned}$$

$$\begin{aligned} \text{Emissions from Centrally Treated Aerobic Systems} &= B \\ &= [(\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times (\% \text{ aerobic}) \times (\% \text{ aerobic w/out primary}) + (\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times (\% \text{ aerobic}) \times (\% \text{ aerobic w/primary}) \times (1\% \text{ BOD removed in prim. treat.})] \times (\% \text{ operations not well managed}) \times (B_o) \times (\text{MCF-aerobic_not_well_man}) \end{aligned}$$

$$\begin{aligned} \text{Emissions from Centrally Treated Anaerobic Systems} &= C \\ &= [(\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times (\% \text{ anaerobic}) \times (\% \text{ anaerobic w/out primary}) + (\% \text{ collected}) \times (\text{total BOD}_5 \text{ produced}) \times (\% \text{ anaerobic}) \times (\% \text{ anaerobic w/primary}) \times (1\% \text{ BOD removed in prim. treat.})] \times (B_o) \times (\text{MCF-anaerobic}) \end{aligned}$$

$$\begin{aligned} \text{Emissions from Anaerobic Digesters} &= D \\ &= [(\text{POTW_flow_AD}) \times (\text{digester gas}) / (\text{per capita flow})] \times \text{conversion to m}^3 \times (\text{FRAC_CH}_4) \times (365.25) \times (\text{density of CH}_4) \times (1\text{-DE}) \times 1/10^9 \end{aligned}$$

$$\text{Total CH}_4 \text{ Emissions (kt)} = A + B + C + D$$

where,

$$\text{USPOP} = \text{U.S. population}$$

% onsite	= Flow to septic systems / total flow
% collected	= Flow to POTWs / total flow
% aerobic	= Flow to aerobic systems / total flow to POTWs
% anaerobic	= Flow to anaerobic systems / total flow to POTWs
% aerobic w/out primary	= Percent of aerobic systems that do not employ primary treatment
% aerobic w/primary	= Percent of aerobic systems that employ primary treatment
% BOD removed in prim. treat.	= 32.5%
% operations not well managed	= Percent of aerobic systems that are not well managed and in which some anaerobic degradation occurs
% anaerobic w/out primary	= Percent of anaerobic systems that do not employ primary treatment
% anaerobic w/primary	= Percent of anaerobic systems that employ primary treatment
EF _{SEPTIC}	= Methane emission factor (10.7 g CH ₄ /capita/day) – septic systems
Days	= days per year (365.25)
Total BOD ₅ produced	= kg BOD/capita/day × U.S. population × 365.25 days/yr
B ₀	= Maximum CH ₄ -producing capacity for domestic wastewater (0.60 kg CH ₄ /kg BOD)
1/10 ⁶	= Conversion factor, kg to kt
MCF-aerobic_not_well_man.	= CH ₄ correction factor for aerobic systems that are not well managed (0.3)
MCF-anaerobic	= CH ₄ correction factor for anaerobic systems (0.8)
DE	= CH ₄ destruction efficiency from flaring or burning in engine (0.99 for enclosed flares)
POTW_flow_AD	= Wastewater influent flow to POTWs that have anaerobic digesters (MGD)
digester gas	= Cubic feet of digester gas produced per person per day (1.0 ft ³ /person/day)
per capita flow conversion to m ³	= Wastewater flow to POTW per person per day (100 gal/person/day)
FRAC_CH ₄	= Conversion factor, ft ³ to m ³ (0.0283)
density of CH ₄	= Proportion CH ₄ in biogas (0.65)
1/10 ⁹	= 662 (g CH ₄ /m ³ CH ₄)
	= Conversion factor, g to kt

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2016) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. Table 7-9 presents U.S. population and total BOD₅ produced for 1990 through 2014, while Table 7-10 presents domestic wastewater CH₄ emissions for both septic and centralized systems in 2014. The proportions of domestic wastewater treated onsite versus at centralized treatment plants were based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, and 2013 *American Housing Surveys* conducted by the U.S. Census Bureau (U.S. Census 2013), with data for intervening years obtained by linear interpolation and data for 2014 forecasted using 1990 to 2013 data. The percent of wastewater flow to aerobic and anaerobic systems, the percent of aerobic and anaerobic systems that do and do not employ primary treatment, and the wastewater flow to POTWs that have anaerobic digesters were obtained from the 1992, 1996, 2000, and 2004 *Clean Watershed Needs Survey* (EPA 1992, 1996, 2000, and 2004). Data for intervening years were obtained by linear interpolation and the years 2004 through 2014 were forecasted from the rest of the time series. The BOD₅ production rate (0.09 kg/capita/day) and the percent BOD₅ removed by primary treatment for domestic wastewater were obtained from Metcalf and Eddy (2003). The maximum CH₄-producing capacity (0.6 kg CH₄/kg BOD₅) and both MCFs used for centralized treatment systems were taken from IPCC (2006), while the CH₄ emission factor (10.7 g CH₄/capita/day) used for septic systems were taken from Leverenz et al. (2010). The CH₄ destruction efficiency for methane recovered from sludge digestion operations, 99 percent, was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in *AP-42 Compilation of Air Pollutant Emission Factors*, Chapter 2.4 (EPA 1998), efficiencies used to establish New Source Performance Standards (NSPS) for landfills, along with data from CAR (2011), Sullivan (2007), Sullivan (2010), and UNFCCC (2012). The cubic feet of digester gas produced per person per day (1.0 ft³/person/day) and the proportion of CH₄ in biogas (0.65) come from Metcalf and Eddy (2003). The wastewater flow to a POTW (100 gal/person/day) was taken from the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, "*Recommended Standards for Wastewater Facilities (Ten-State Standards)*" (2004).

Table 7-9: U.S. Population (Millions) and Domestic Wastewater BOD₅ Produced (kt)

Year	Population	BOD ₅
1990	253	8,333
2005	300	9,853
2010	313	10,304
2011	316	10,381
2012	318	10,459
2013	321	10,536
2014	323	10,613

Sources: U.S. Census Bureau (2016); Metcalf & Eddy (2003).

Table 7-10: Domestic Wastewater CH₄ Emissions from Septic and Centralized Systems (2014, MMT CO₂ Eq. and Percent)

	CH ₄ Emissions (MMT CO ₂ Eq.)	% of Domestic Wastewater CH ₄
Septic Systems	5.9	65.8%
Centralized Systems (including anaerobic sludge digestion)	3.1	34.2%
Total	9.0	100%

Note: Totals may not sum due to independent rounding.

Industrial Wastewater CH₄ Emission Estimates

Methane emission estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH₄ emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify these industries 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 CH₄ emissions. The top five industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; and petroleum refining. Wastewater treatment emissions for these sectors for 2014 are displayed in Table 7-11 below. Table 7-12 contains production data for these industries.

Table 7-11: Industrial Wastewater CH₄ Emissions by Sector (2014, MMT CO₂ Eq. and Percent)

	CH ₄ Emissions (MMT CO ₂ Eq.)	% of Industrial Wastewater CH ₄
Meat & Poultry	4.3	76%
Pulp & Paper	1.0	17%
Fruit & Vegetables	0.1	3%
Petroleum Refineries	0.1	3%
Ethanol Refineries	0.1	2%
Total	5.7	100%

Note: Totals may not sum due to independent rounding.

Table 7-12: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, and Petroleum Refining Production (MMT)

Year	Pulp and Paper ^a	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.5	702.4
2005	138.5	31.4	25.1	42.9	11.7	818.6
2010	126.7	33.7	25.9	43.2	39.7	848.6
2011	126.1	33.8	26.2	44.3	41.6	858.8
2012	124.4	33.8	26.1	45.6	39.5	856.1
2013	122.8	33.6	26.5	45.1	39.8	878.7
2014	120.9	32.2	26.9	45.6	42.8	903.9

^aPulp and paper production is the sum of woodpulp production plus paper and paperboard production.

Sources: Lockwood-Post (2002); FAO (2016); USDA (2016a); RFA (2016); EIA (2016).

Methane emissions from these categories were estimated by multiplying the annual product output by the average outflow, the organics loading (in COD) in the outflow, the maximum CH₄ producing potential of industrial wastewater (B_o), and the percentage of organic loading assumed to degrade anaerobically in a given treatment system (MCF). Ratios of BOD:COD in various industrial wastewaters were obtained from EPA (1997a) and used to estimate COD loadings. The B_o value used for all industries is the IPCC default value of 0.25 kg CH₄/kg COD (IPCC 2006).

For each industry, the percent of plants in the industry that treat wastewater on site, the percent of plants that have a primary treatment step prior to biological treatment, and the percent of plants that treat wastewater anaerobically were defined. The percent of wastewater treated anaerobically onsite (TA) was estimated for both primary treatment (%TA_p) and secondary treatment (%TA_s). For plants that have primary treatment in place, an estimate of COD that is removed prior to wastewater treatment in the anaerobic treatment units was incorporated. The values used in the %TA calculations are presented in Table 7-13 below.

The methodological equations are:

$$\text{CH}_4 \text{ (industrial wastewater)} = [P \times W \times \text{COD} \times \% \text{TA}_p \times B_o \times \text{MCF}] + [P \times W \times \text{COD} \times \% \text{TA}_s \times B_o \times \text{MCF}]$$

$$\% \text{TA}_p = [\% \text{Plants}_o \times \% \text{WW}_{a,p} \times \% \text{COD}_p]$$

$$\% \text{TA}_s = [\% \text{Plants}_a \times \% \text{WW}_{a,s} \times \% \text{COD}_s] + [\% \text{Plants}_t \times \% \text{WW}_{a,t} \times \% \text{COD}_s]$$

where,

CH ₄ (industrial wastewater)	= Total CH ₄ emissions from industrial wastewater (kg/year)
P	= Industry output (metric tons/year)
W	= Wastewater generated (m ³ /metric ton of product)
COD	= Organics loading in wastewater (kg/m ³)
% TA _p	= Percent of wastewater treated anaerobically on site in primary treatment
% TA _s	= Percent of wastewater treated anaerobically on site in secondary treatment
% Plants _o	= Percent of plants with onsite treatment
% WW _{a,p}	= Percent of wastewater treated anaerobically in primary treatment
% COD _p	= Percent of COD entering primary treatment
% Plants _a	= Percent of plants with anaerobic secondary treatment
% Plants _t	= Percent of plants with other secondary treatment
% WW _{a,s}	= Percent of wastewater treated anaerobically in anaerobic secondary treatment
% WW _{a,t}	= Percent of wastewater treated anaerobically in other secondary treatment
% COD _s	= Percent of COD entering secondary treatment
B _o	= Maximum CH ₄ producing potential of industrial wastewater (default value of 0.25 kg CH ₄ /kg COD)
MCF	= CH ₄ correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically

Alternate methodological equations for calculating %TA were used for secondary treatment in the pulp and paper industry to account for aerobic systems with anaerobic portions. These equations are:

$$\%TA_a = [\%Plants_a \times \%WW_{a,s} \times \%COD_s] + [\%Plant_{st} \times \%WW_{at} \times COD_s]$$

$$\%TA_{at} = [\%Plants_{at} \times \%WW_{a,s} \times \%COD_s]$$

where,

$\%TA_a$	= Percent of wastewater treated anaerobically on site in secondary treatment
$\%TA_{at}$	= Percent of wastewater treated in aerobic systems with anaerobic portions on site in secondary treatment
$\%Plants_a$	= Percent of plants with anaerobic secondary treatment
$\%Plants_{a,t}$	= Percent of plants with partially anaerobic secondary treatment
$\%WW_{a,s}$	= Percent of wastewater treated anaerobically in anaerobic secondary treatment
$\%WW_{a,t}$	= Percent of wastewater treated anaerobically in other secondary treatment
$\%COD_s$	= Percent of COD entering secondary treatment

As described below, the values presented in Table 7-13 were used in the emission calculations and are described in detail in ERG (2008), ERG (2013a), and ERG (2013b).

Table 7-13: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry (percent)

Variable	Industry						
	Pulp and Paper	Meat Processing	Poultry Processing	Fruit/Vegetable Processing	Ethanol Production – Wet Mill	Ethanol Production – Dry Mill	Petroleum Refining
%TA _p	0	0	0	0	0	0	0
%TA _s	0	33	25	4.2	33.3	75	23.6
%TA _a	2.2	0	0	0	0	0	0
%TA _{a,t}	11.8	0	0	0	0	0	0
%Plants _o	0	100	100	11	100	100	100
%Plants _a	5	33	25	5.5	33.3	75	23.6
%Plants _{a,t}	28	0	0	0	0	0	0
%Plants _{st}	35	67	75	5.5	66.7	25	0
%WW _{a,p}	0	0	0	0	0	0	0
%WW _{a,s}	100	100	100	100	100	100	100
%WW _{a,t}	0	0	0	0	0	0	0
%COD _p	100	100	100	100	100	100	100
%COD _s	42	100	100	77	100	100	100

Sources: ERG (2008); ERG (2013a); and ERG (2013b).

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. In determining the percent that degrades anaerobically, both primary and secondary treatment were considered. In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993). 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 1993). However, because the vast majority of primary treatment operations at U.S. pulp and paper mills use mechanical clarifiers, and less than 10 percent of pulp and paper wastewater is managed in primary settling ponds that are not expected to have anaerobic conditions, negligible emissions are assumed to occur during primary treatment.

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Based on EPA's *OAQPS Pulp and Paper Sector Survey*, 5.3 percent of pulp and paper mills reported using anaerobic secondary treatment for wastewater and/or pulp

condensates (ERG 2013a). Twenty-eight percent of mills also reported the use of quiescent settling ponds. Using engineering judgment, these systems were determined to be aerobic with possible anaerobic portions. For the truly anaerobic systems, an MCF of 0.8 is used, as these are typically deep stabilization basins. For the partially anaerobic systems, an MCF of 0.2 is used, which is the IPCC suggested MCF for shallow lagoons.

A time series of CH₄ emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Data from the Food and Agricultural Organization of the United Nations (FAO) database FAOSTAT were used for 2002 through 2014 (FAO 2016). The overall wastewater outflow varies based on a time series outlined in ERG (2013a) to reflect historical and current industry wastewater flow, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b; EPA 1993; World Bank 1999). The COD:BOD ratio used to convert the organic loading to COD for pulp and paper mills was 2 (EPA 1997a).

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. 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 B₀ of 0.25 kg CH₄/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH₄ produced from these on-site treatment systems. Production data, in carcass weight and live weight killed for the meat and poultry industry, were obtained from the USDA *Agricultural Statistics Database and the Agricultural Statistics Annual Reports* (USDA 2016a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m³/metric ton for meat and poultry production (live weight killed), respectively (EPA 2002). The loadings are 2.8 and 1.5 g BOD/liter for meat and poultry, respectively. The COD:BOD ratio used to convert the organic loading to COD for both meat and poultry facilities was 3 (EPA 1997a).

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. Effluent is suitable for discharge to the sewer. This industry is likely to 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). Consequently, 4.2 percent of these wastewater organics are assumed to degrade anaerobically. The IPCC default B₀ of 0.25 kg CH₄/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH₄ produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2016a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 7-14, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors. The COD:BOD ratio used to convert the organic loading to COD for all fruit, vegetable, and juice facilities was 1.5 (EPA 1997a).

Table 7-14: Wastewater Flow (m³/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m ³ /ton)	BOD (g/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	8.60	0.784
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

Sources: 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

only about 2 percent of ethanol production, and although the U.S. Department of Energy (DOE) predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage 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 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 has become more efficient in recent years (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 digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006).

Available information was compiled from the industry on wastewater generation rates, which ranged from 1.25 gallons per gallon ethanol produced (for dry milling) to 10 gallons per gallon ethanol produced (for wet milling) (Ruocco 2006a; Ruocco 2006b; Merrick 1998; Donovan 1996; NRPB 2001). COD concentrations were also found to be about 3 g/L (Ruocco 2006a; Merrick 1998; White and Johnson 2003). The amount of wastewater treated anaerobically was estimated, along with how much of the CH₄ is recovered through the use of biomethanators. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006). Methane emissions were then estimated as follows:

$$\text{Methane} = [\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times ([\% \text{Plants}_o \times \% \text{WW}_{a,p} \times \% \text{COD}_p] + [\% \text{Plants}_a \times \% \text{WW}_{a,s} \times \% \text{COD}_s] + [\% \text{Plants}_t \times \% \text{WW}_{a,t} \times \% \text{COD}_s]) \times B_o \times MCF \times \% \text{ Not Recovered}] + [\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times ([\% \text{Plants}_o \times \% \text{WW}_{a,p} \times \% \text{COD}_p] + [\% \text{Plants}_a \times \% \text{WW}_{a,s} \times \% \text{COD}_s] + [\% \text{Plants}_t \times \% \text{WW}_{a,t} \times \% \text{COD}_s]) \times B_o \times MCF \times (\% \text{ Recovered}) \times (1-\text{DE})] \times 1/10^9$$

where,

Production	= gallons ethanol produced (wet milling or dry milling)
Flow	= gallons wastewater generated per gallon ethanol produced (1.25 dry milling, 10 wet milling)
COD	= COD concentration in influent (3 g/l)
3.785	= conversion, gallons to liters
% Plants _o	= percent of plants with onsite treatment (100%)
% WW _{a,p}	= percent of wastewater treated anaerobically in primary treatment (0%)
% COD _p	= percent of COD entering primary treatment (100%)
% Plants _a	= percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)
% Plants _t	= percent of plants with other secondary treatment (66.7% wet, 25% dry)
% WW _{a,s}	= percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)
% WW _{a,t}	= percent of wastewater treated anaerobically in other secondary treatment (0%)
% COD _s	= percent of COD entering secondary treatment (100%)
B _o	= maximum methane producing capacity (0.25 g CH ₄ /g COD)
MCF	= methane conversion factor (0.8 for anaerobic systems)
% Recovered	= percent of wastewater treated in system with emission recovery
% Not Recovered	= 1 - percent of wastewater treated in system with emission recovery
DE	= destruction efficiency of recovery system (99%)
1/10 ⁹	= conversion factor, g to kt

A time series of CH₄ emissions for 1990 through 2014 was developed based on production data from the Renewable Fuels Association (RFA 2016).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH₄ emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.⁸ Of the responding facilities, 23.6 percent reported using

⁸ Available online at <<https://refineryicr.rti.org/>>.

non-aerated surface impoundments or other biological treatment units, both of which have the potential to lead to anaerobic conditions (ERG 2013b). In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product (ERG 2013b). An average COD value in the wastewater was estimated at 0.45 kg/m³ (Benyahia et al. 2006).

The equation used to calculate CH₄ generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times \text{TA} \times B_o \times \text{MCF}$$

where,

Flow	= Annual flow treated through anaerobic treatment system (m ³ /year)
COD	= COD loading in wastewater entering anaerobic treatment system (kg/m ³)
TA	= Percent of wastewater treated anaerobically on site
B _o	= maximum methane producing potential of industrial wastewater (default value of 0.25 kg CH ₄ /kg COD)
MCF	= methane conversion factor (0.3)

A time series of CH₄ emissions for 1990 through 2014 was developed based on production data from the Energy Information Association (EIA 2016).

Domestic Wastewater N₂O Emission Estimates

Nitrous oxide emissions from domestic wastewater (wastewater treatment) were estimated using the IPCC (2006) methodology, including calculations that take into account N removal with sewage sludge, non-consumption and industrial/commercial wastewater N, and emissions from advanced centralized wastewater treatment plants:

- In the United States, a certain amount of N is removed with sewage sludge, which is applied to land, incinerated, or landfilled (N_{SLUDGE}). The N disposal into aquatic environments is reduced to account for the sewage sludge application.
- The IPCC methodology uses annual, per capita protein consumption (kg protein/person-year). For this Inventory, the amount of protein available to be consumed is estimated based on per capita annual food availability data and its protein content, and then adjusts that data using a factor to account for the fraction of protein actually consumed.
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N gas in anoxic biological treatment systems. Approximately 7 g N₂O is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001). Analysis of the 2004 CWNS shows that plants with denitrification as one of their unit operations serve a population of 2.4 million people. Based on an emission factor of 7 g per capita per year, approximately 21.2 metric tons of additional N₂O may have been emitted via denitrification in 2004. Similar analyses were completed for each year in the Inventory using data from CWNS on the amount of wastewater in centralized systems treated in denitrification units. Plants without intentional nitrification/denitrification are assumed to generate 3.2 g N₂O per capita per year.

Nitrous oxide emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [(US_{POPND}) \times EF_2 \times F_{IND-COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND}] \times F_{IND-COM} \times EF_1\} \times 1/10^9$$

$$N_2O_{EFFLUENT} = \{[((US_{POP} \times WWTP) - (0.9 \times US_{POPND})) \times Protein \times FNPR \times F_{NON-CON} \times F_{IND-COM}] - N_{SLUDGE}\} \times EF_3 \times 44/28 \times 1/10^6$$

where,

$$N_2O_{TOTAL} = \text{Annual emissions of } N_2O \text{ (kt)}$$

N_2O_{PLANT}	= N_2O emissions from centralized wastewater treatment plants (kt)
$N_2O_{NIT/DENIT}$	= N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kt)
$N_2O_{WOUT\ NIT/DENIT}$	= N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kt)
$N_2O_{EFFLUENT}$	= N_2O emissions from wastewater effluent discharged to aquatic environments (kt)
US_{POP}	= U.S. population
US_{POPND}	= U.S. population that is served by biological denitrification (from CWNS)
$WWTP$	= Fraction of population using WWTP (as opposed to septic systems)
EF_1	= Emission factor (3.2 g N_2O /person-year) – plant with no intentional denitrification
EF_2	= Emission factor (7 g N_2O /person-year) – plant with intentional denitrification
$Protein$	= Annual per capita protein consumption (kg/person/year)
F_{NPB}	= Fraction of N in protein, default = 0.16 (kg N/kg protein)
$F_{NON-CON}$	= Factor for non-consumed protein added to wastewater (1.4)
$F_{IND-COM}$	= Factor for industrial and commercial co-discharged protein into the sewer system (1.25)
N_{SLUDGE}	= N removed with sludge, kg N/yr
EF_3	= Emission factor (0.005 kg N_2O -N/kg sewage-N produced) – from effluent
0.9	= Amount of nitrogen removed by denitrification systems
44/28	= Molecular weight ratio of N_2O to N_2

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2016) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011, and 2013 *American Housing Survey* (U.S. Census 2013). Data for intervening years were obtained by linear interpolation and data from 2014 were forecasted using 1990 to 2013 data. The emission factor (EF_1) used to estimate emissions from wastewater treatment for plants without intentional denitrification was taken from IPCC (2006), while the emission factor (EF_2) used to estimate emissions from wastewater treatment for plants with intentional denitrification was taken from Scheehle and Doorn (2001). Data on annual per capita protein intake were provided by the U.S. Department of Agriculture Economic Research Service (USDA 2016b). Protein consumption data for 2011 through 2014 were extrapolated from data for 1990 through 2010. An emission factor to estimate emissions from effluent (EF_3) has not been specifically estimated for the United States, thus the default IPCC value (0.005 kg N_2O -N/kg sewage-N produced) was applied (IPCC 2006). The fraction of N in protein (0.16 kg N/kg protein) was also obtained from IPCC (2006). The factor for non-consumed protein and the factor for industrial and commercial co-discharged protein were obtained from IPCC (2006). Sludge generation was obtained from EPA (1999) for 1988, 1996, and 1998 and from Beecher et al. (2007) for 2004. Intervening years were interpolated, and estimates for 2005 through 2014 were forecasted from the rest of the time series. The amount of nitrogen removed by denitrification systems was taken from EPA (2008). An estimate for the N removed as sludge (N_{SLUDGE}) was obtained by determining the amount of sludge disposed by incineration, by land application (agriculture or other), through surface disposal, in landfills, or through ocean dumping (US EPA 1993b; Beecher et al. 2007; McFarland 2001; US EPA 1999). In 2014, 289 kt N was removed with sludge. Table 7-15 presents the data for U.S. population, population served by biological denitrification, population served by wastewater treatment plants, available protein, protein consumed, and nitrogen removed with sludge.

Table 7-15: U.S. Population (Millions), Population Served by Biological Denitrification (Millions), Fraction of Population Served by Wastewater Treatment (percent), Available Protein (kg/person-year), Protein Consumed (kg/person-year), and Nitrogen Removed with Sludge (kt-N/year)

Year	Population	Population _{ND}	WWTP Population	Available Protein	Protein Consumed	N Removed
1990	253	2.0	75.6	43.1	33.2	214.2
2005	300	2.7	78.8	44.9	34.7	261.1
2010	313	3.0	80.0	43.8	33.7	276.4
2011	316	3.0	80.6	45.0	34.7	279.5

2012	318	3.0	81.0	45.1	34.7	282.6
2013	321	3.1	81.4	45.1	34.8	285.6
2014	323	3.1	81.1	45.2	34.8	288.7

Sources: Beecher et al. (2007); McFarland (2001); U.S. Census (2013); U.S. Census (2016); USDA (2016b); US EPA (1992); US EPA (1993b); US EPA (1996); US EPA (1999); US EPA (2000); US EPA (2004).

Uncertainty and Time-Series Consistency

The overall uncertainty associated with both the 2014 CH₄ and N₂O 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 CH₄ emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruits and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N₂O emissions include that of sewage sludge disposal, total U.S. population, average protein consumed per person, fraction of N in protein, non-consumption nitrogen factor, emission factors per capita and per mass of sewage-N, and for the percentage of total population using centralized wastewater treatment plants.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-16. Methane emissions from wastewater treatment were estimated to be between 9.0 and 15.0 MMT CO₂ Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 39 percent below to 2 percent above the 2014 emissions estimate of 14.7 MMT CO₂ Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 1.1 and 10.1 MMT CO₂ Eq., which indicates a range of approximately 76 percent below to 108 percent above the 2014 emissions estimate of 4.8 MMT CO₂ Eq.

Table 7-16: Approach 2 Quantitative Uncertainty Estimates for CH₄ Emissions from Wastewater Treatment (MMT CO₂ Eq. and Percent)

Source	Gas	2014 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
Wastewater Treatment	CH₄	14.7	9.0	15.0	-39%	+2%
Domestic	CH ₄	9.0	5.7	9.7	-37%	+8%
Industrial	CH ₄	5.7	2.4	6.8	-58%	+20%
Wastewater Treatment	N₂O	4.8	1.1	10.1	-76%	+108%

^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 2014. Details on the emission trends through time are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed on activity data, documentation, and emission calculations. This effort included a 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 emissions estimates trends; and
- Compared estimates to previous estimates to identify significant changes.

All transcription errors identified were corrected. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

Recalculations Discussion

Production data were updated to reflect revised U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) datasets. Updates to meat and poultry data based on changes to the 2012 *Census for Agriculture* and 2013 and 2014 annual revisions resulted in animal population changes for beef from 2008 to 2013, veal from 2009 to 2013, and lamb and muttons in 2009 (Bertramson 2016). In addition, the most recent USDA Economic Research Service (ERS) data were used to update protein data values from 1990 through 2010. The updated ERS data also resulted in changes in forecasted values from 2011 (Cooper 2014).

The estimated number of ethanol plants using dry milling versus wet milling were updated for 1990 to 2014 with data provided by Renewable Fuels Association (RFA) (Cooper 2014). This change resulted in updated values for ethanol produced (both dry and wet) for the entire time series.

Planned Improvements

Due to circumstances, only very limited improvements were made to the wastewater treatment section of this Inventory. As a result, the planned improvements detailed previously will continue to be investigated for possible inclusion in a future Inventory. Below is a brief summary of ongoing investigations.

- EPA is continuing its evaluation of Greenhouse Gas Reporting Program (GHGRP) reports for improvements to activity data and for verifying methodologies currently in use in the Inventory to estimate emissions.
- EPA is working with the National Council of Air and Stream Improvement (NCASI) to determine if there are sufficient data available to update the estimates of organic loading in pulp and paper wastewaters treated on-site.
- EPA is investigating the inclusion of constructed and semi-natural treatment wetlands in Inventory calculations using IPCC's 2013 wetlands supplement (IPCC 2014) using CWNS treatment system data or other data sources.
- EPA is continuing its review of other industrial wastewater treatment sources for those industries believed to discharge significant loads of BOD and COD, including dairy processing wastewater.

Over the longer term, potential sources for updating inventory data continue to be monitored, including:

- Updated sources of activity data for wastewater treatment system type to distinguish between aerobic, anaerobic, and aerobic systems with the potential to generate CH₄;
- Water Environment Federation (WEF) biosolid data as a potential source of digester, sludge, and biogas data from POTWs;
- Reports based on international research and other countries' inventory submissions to inform potential updates to the Inventory's emission factors, methodologies, or included industries;
- Research by groups such as the Water Environment Research Federation (WERF) on emissions from various types of municipal treatment systems, country-specific N₂O emission factors, and flare efficiencies;
- Sources of data for development of a country-specific methodology for N₂O emissions associated with on-site industrial wastewater treatment operations, including the appropriateness of using IPCC's default factor for domestic wastewater (0.005 kg N₂O-N/kg N);
- Data collected by WERF that indicate septic soil systems are a source of N₂O for the potential development of appropriate emission factors for septic system N₂O emissions;
- Additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems; and
- Data to update the value used for N content of sludge, the amount of sludge produced, and sludge disposal practices, along with increasing the transparency of the fate of sludge produced in wastewater treatment.

See Section 7.2 of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 through 2013* for full detail of these planned improvements.

7.3 Composting (IPCC 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. Advantages of composting include reduced volume of the waste, stabilization of the waste, and destruction of pathogens in the waste. The end products of composting, depending on its quality, can be recycled as a fertilizer and soil amendment, or be disposed of in a landfill.

Composting is an aerobic process and a large fraction of the degradable organic carbon in the waste material is converted into carbon dioxide (CO_2). Methane (CH_4) is formed in anaerobic sections of the compost, which are created when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. 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 one percent to a few percent of the initial carbon (C) content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can 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 later composting stages. 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.

From 1990 to 2014, the amount of waste composted in the United States has increased from 3,810 kt to 20,533 kt, an increase of approximately 439 percent. The amount of material composted in the United States in the last decade has increased by approximately 11 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage. In 2014, CH_4 emissions from composting (see Table 7-17 and Table 7-18) were 2.1 MMT CO_2 Eq. (82 kt), and N_2O emissions from composting were 1.8 MMT CO_2 Eq. (6 kt). 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 backyard composting or agricultural composting.

The growth in composting since the 1990s and specifically over the past decade is attributable to primarily three factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, and (3) an increased awareness of the environmental benefits of composting. Most bans on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). By 2010, 25 states, representing about 50 percent of the nation's population, had enacted such legislation (BioCycle 2010). An additional 16 states are known to have commercial-scale composting facilities (Shin 2014). Despite these factors, the total amount of waste composted exhibited a downward trend after peaking in 2008 (see Table 7-17 and Figure 7-5), but has been increasing since 2010 and the annual quantity composted is now on par with the 2008 quantity composted. While there is no definitive reason for the decreasing trend in the amount of waste composted, it is most likely a result of the recession and the fact that the quantities composted are estimated using a mass balance approach on the municipal waste stream across the entire United States. As presented in Figure 7-5, the quantity of CH_4 and N_2O emitted from composting operations across the time-series parallels the trends for the quantities composted, although the trend in emissions has a much lower slope compared to the quantities composted.

Table 7-17: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

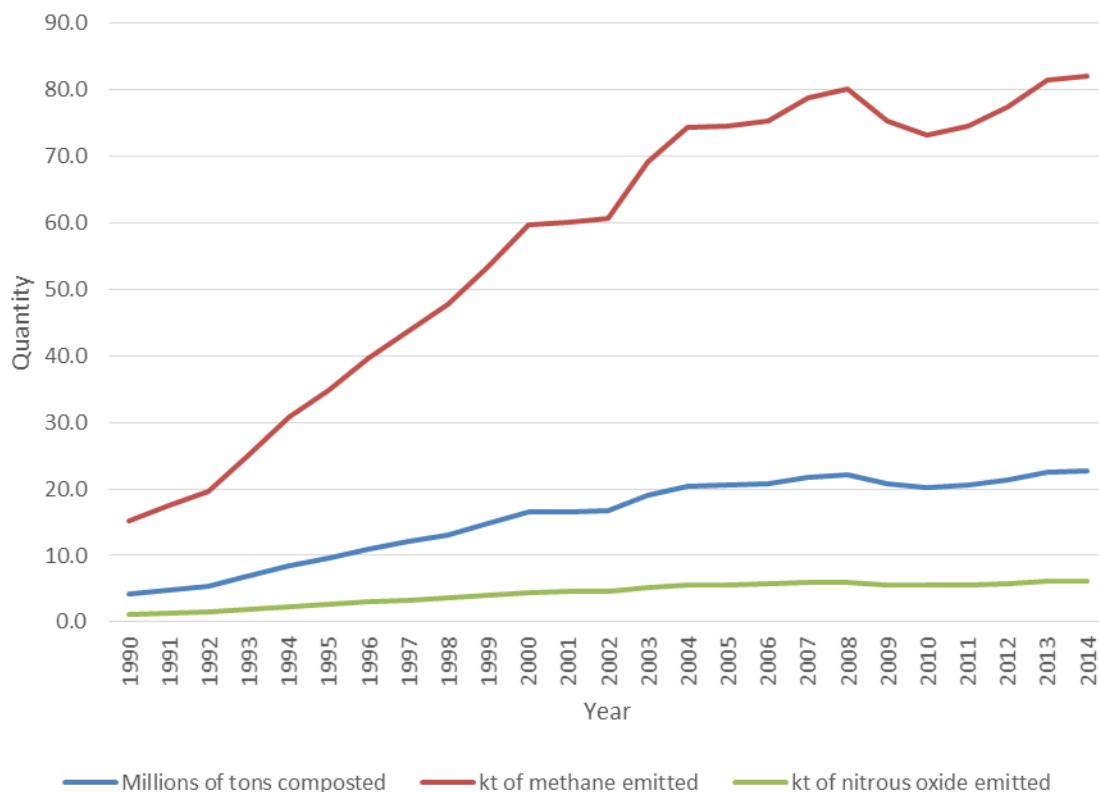
Activity	1990	2005	2010	2011	2012	2013	2014
CH_4	0.4	1.9	1.8	1.9	1.9	2.0	2.1
N_2O	0.3	1.7	1.6	1.7	1.7	1.8	1.8
Total	0.7	3.5	3.5	3.5	3.7	3.9	3.9

Note: Totals may not sum due to independent rounding.

Table 7-18: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
CH_4	15	75	73	75	77	81	82
N_2O	1	6	5	6	6	6	6

Figure 7-5: CH₄ and N₂O Emitted from Composting Operations between 1990 and 2014 (kt or million tons)



Methodology

Methane and N₂O 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 emissions shown in Table 7-17 and Table 7-18 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 CH₄ 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 ₂ O emissions from composting, kt CH ₄ or N ₂ O
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 ₂ O/kt of waste treated (wet basis) (IPCC 2006)
i	=	designates either CH ₄ or N ₂ O

Estimates of the quantity of waste composted (M) are presented in Table 7-19. Estimates of the quantity composted for 1990, 2005 and 2007 through 2009 were taken from EPA's *Municipal Solid Waste in the United States: 2010 Facts and Figures* (EPA 2011); estimates of the quantity composted for 2006 were taken from EPA's *Municipal Solid Waste In The United States: 2006 Facts and Figures* (EPA 2007); estimates of the quantity composted for 2011 through 2012 were taken from EPA's *Municipal Solid Waste In The United States: 2012 Facts and Figures* (EPA 2014); estimates of the quantity composted for 2013 was taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013* (EPA 2015); and estimates of the quantity composted for 2014 were

extrapolated using the 2013 quantity composted and a ratio of the U.S. population in 2013 and 2014 (U.S. Census Bureau 2015).

Table 7-19: U.S. Waste Composted (kt)

Activity	1990	2005	2010	2011	2012	2013	2014
Waste Composted	3,810	18,643	18,298	18,661	19,351	20,358	20,533

Uncertainty and Time-Series Consistency

The estimated uncertainty from the *2006 IPCC Guidelines* is ±50 percent for the Approach 1 methodology. Emissions from composting in 2014 were estimated to be between 1.9 and 5.8 MMT CO₂ Eq., which indicates a range of 50 percent below to 50 percent above the actual 2014 emission estimate of 3.9 MMT CO₂ Eq. (see Table 7-20).

Table 7-20: Approach 1 Quantitative Uncertainty Estimates for Emissions from Composting (MMT CO₂ Eq. and Percent)

Source	Gas	2014 Emission Estimate (MMT CO ₂ Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO ₂ Eq.)			
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH ₄ , N ₂ O	3.9	1.9	5.8	-50%	+50%

Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. Details on the emission trends through time-series are described in more detail in the Methodology section, above.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. A primary focus of the QA/QC checks was to ensure that the amount of waste composted annually was correct according to the latest EPA *Advancing Sustainable Materials Management: Facts and Figures* report.

Recalculations Discussion

The estimated amount of waste composted in 2013 was updated based on new data contained in EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013* report (EPA 2015) relative to the previous report. The amounts of CH₄ and N₂O emission estimates presented in Table 7-17 and Table 7-18 were revised accordingly.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH₄ and N₂O emissions from composting. For example, a literature search on emission factors and their drivers (e.g., the type of composting system, material composition, management technique, impact of varying climatic regions) is underway. The purpose of this literature review is to compile all published emission factors to determine whether the emission factors used in the current methodology should be revised, or expanded to account for various composting system, material composition, management techniques, and/or geographical/climatic differences. For example, composting systems that primarily compost food waste may generate CH₄ at different rates than composting yard trimmings because the food waste may have a higher moisture content and more readily degradable material. Further cooperation with estimating emissions in the Land Use, Land-Use Change, and Forestry (LULUCF) Other section will also be investigated.

7.4 Waste Incineration (IPCC Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) 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 2014 resulted in 9.7 MMT CO₂ Eq. emissions, over half of which (4.9 MMT CO₂ 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 CO₂ 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.

7.5 Waste Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of indirect greenhouse gas emissions. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH₄ volatile organic compounds (NMVOCs) from waste sources for the years 1990 through 2014 are provided in Table 7-21.

Table 7-21: Emissions of NO_x, CO, and NMVOC from Waste (kt)

Gas/Source	1990	2005	2010	2011	2012	2013	2014
NO _x	+	2	1	1	1	1	1
Landfills	+	2	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous ^a	+	0	0	0	0	0	0
CO	1	7	5	5	5	5	5
Landfills	1	6	5	4	4	4	4
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous ^a	+	0	0	0	0	0	0
NMVOCs	673	114	44	38	38	38	39
Wastewater Treatment	57	49	19	17	17	17	17
Miscellaneous ^a	557	43	17	15	15	15	15
Landfills	58	22	8	7	7	7	7

+ Does not exceed 0.5 kt.

^aMiscellaneous 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.

Note: Totals may not sum due to independent rounding.

Methodology

Emission estimates for 1990 through 2014 were obtained from data published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site (EPA 2015), and disaggregated based on EPA (2003). Emission estimates for 2014 for non-electric generating unit (EGU) and non-mobile sources are held constant from 2011 in EPA (2015). 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 2014. 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, emission and sink estimates are recalculated and revised for all years in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, as attempts are made to improve both the analyses themselves, through the use of better methods or data, and the 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; new inventory methods become available; and for correction of errors.”

The results of all methodological changes and historical data updates made in the current Inventory report are presented in this section; detailed descriptions of each recalculation are contained within each source’s description found in this report, if applicable. Table 9-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and sinks and Table 9-2 summarizes the quantitative effect on annual net CO₂ fluxes, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2013 report). These tables present the magnitude of these changes in units of million metric tons of carbon dioxide equivalent (MMT CO₂ Eq.).

The Recalculations Discussion section of each source’s description in the respective chapter of this Inventory presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2013) has been recalculated to reflect the change, per IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

The following ten emission sources and sinks underwent some of the most significant methodological and historical data changes. These emission sources consider only methodological and historical data changes. A brief summary of the recalculations and/or improvements undertaken is provided for each of the ten sources.

- *Natural Gas Systems (CH₄)*. EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories’ formal public notice periods, GHGRP data, and new studies. EPA carefully evaluated relevant information available, and made several updates, including revisions to production segment activity data, production segment pneumatic controller activity and emissions data, gathering and boosting facility emissions, transmission and storage station activity and emissions data, distribution segment emissions data for pipelines, distribution segment M&R station activity and emissions data, and distribution segment customer meter emissions data. From December 2015 through February 2016, the EPA released four draft memos that discussed the changes under consideration and requested stakeholder feedback on those changes. The impact of all revisions to natural gas systems is an average annual increase in emissions of 12.9 MMT CO₂ Eq. relative to the previous Inventory.
- *Petroleum Systems (CH₄)*. The EPA received information and data related to the emission estimates through the Inventory preparation process, previous Inventories’ formal public notice periods, EPA’s Greenhouse Gas Reporting Program (GHGRP) data, and new studies. The EPA carefully evaluated relevant information available, and made revisions to the production segment methodology for the 2016 Inventory including revised equipment activity data, revised pneumatic controller activity and emissions data, and included a separate estimate for hydraulically fractured oil completions, which were previously not estimated as a distinct subcategory of oil well completions. All these changes resulted in an average annual increase in emissions of 20.7 MMT CO₂ Eq. relative to the previous Inventory.

- *Landfills (CH₄)*. Four major methodological recalculations were performed for the current Inventory. First, a rigorous review of the flare and landfill gas-to-energy (LFGTE) projects across the four recovery databases was conducted. Extensive corrections were made to avoid double counting of projects across the recovery databases. Additionally, several facilities in the LFGTE database were removed because they were not in the published LMOP database for the current or past two years (EPA 2015). Second, the GHGRP CH₄ recovery data were back-calculated for landfills in the GHGRP database for years prior to the first GHGRP reporting year (typically 2010 for most landfills). Third, the flare correction factor was revised. Fourth, the DOC value for landfilled pulp and paper waste was revised from 0.20 to 0.15 based a literature review of pulp and paper waste characterization studies (RTI 2015) and data reported under the GHGRP. The overall impact to the Inventory from these changes resulted in an average increase of nearly 14 percent across the time series. A significant increase in net CH₄ emissions for the years 2010 through 2013 ranging from 20 to 52 percent higher in the current inventory compared to the 1990 to 2013 inventory. These changes resulted in an average annual decrease in emissions of 6.4 MMT CO₂ Eq. relative to the previous Inventory.
- *Agricultural Soil Management (N₂O)*. Methodological recalculations in the current Inventory are associated with the following improvements: (1) driving the DAYCENT simulations with updated input data for land management from the National Resources Inventory extending the time series through 2010; (2) accounting for N inputs from residues associated with additional crops not simulated by DAYCENT including most vegetable crops; (3) modifying the number of experimental study sites used to quantify model uncertainty for direct N₂O emissions; and (4) using DAYCENT for direct N₂O emissions from most flooded rice lands, instead of using the Tier 1 approach for all rice lands. These changes resulted in an increase in emissions of approximately 24 percent on average relative to the previous Inventory and a decrease in the upper bound of the 95 percent confidence interval for direct N₂O emissions from 26 to 24 percent. The differences in emissions and uncertainty are mainly due to increasing the number of study sites used to quantify model uncertainty. These changes resulted in an average annual increase in emissions of 60.1 MMT CO₂ Eq. relative to the previous Inventory.
- *Land Converted to Grassland - Changes in Agricultural Soil Carbon Stocks (CO₂)*. Methodological recalculations in the current Inventory are associated with the following improvements, including: (1) incorporation of updated NRI data for 1990 through 2010; (2) inclusion of federal grasslands in the Tier 2 analysis; (3) improving the simulation of hydric soils in DAYCENT, and (4) incorporating the aboveground biomass C stock losses with Forest Land Converted to Grassland. These changes resulted in an average annual increase in emissions of 49.0 MMT CO₂ Eq. relative to the previous Inventory.
- *Land Converted to Cropland - Changes in Agricultural Carbon Stocks (CO₂)*. Methodological recalculations in the current Inventory are associated with the following improvements: (1) incorporation of updated NRI data for 1990 through 2010; (2) inclusion of federal croplands; (3) improving the simulation of hydric soils in DAYCENT, and (4) incorporating the aboveground biomass C stock losses with Forest Land Converted to Cropland. These changes in SOC stocks resulted in an average annual decrease in emissions of 21.8 MMT CO₂ Eq. relative to the previous Inventory.
- *Cropland Remaining Cropland - Changes in Agricultural Carbon Stocks (CO₂ sink)*. Methodological recalculations in the current Inventory are associated with the following improvements: (1) incorporation of updated NRI data for 1990 through 2010; and (2) inclusion of federal croplands; and (3) improving the simulation of hydric soil. These changes in SOC stocks resulted in an average annual decrease in sequestration of 16.5 MMT CO₂ Eq. relative to the previous Inventory.
- *Forest Land Remaining Forest Land - Changes in Forest Carbon Stock (CO₂ sink)*. Forest ecosystem stock and stock-change estimates differ from the previous Inventory report principally due to the adoption of a new accounting framework (Woodall et al. 2015). The major differences between the framework used this year and past accounting approaches is the sole use of annual FIA data and the back-casting of forest C stocks across the 1990s based on forest C stock density and land use change information obtained from the nationally consistent annual forest inventory coupled with in situ observations of non-tree C pools such as soils, dead wood, and litter. The use of this accounting framework has enabled the creation of the two land use sections for forest C stocks: *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. In prior submissions (e.g., the 1990 through 2013 Inventory submission), the C stock changes from *Land Converted to Forest Land* were a part of the *Forest Land Remaining Forest Land* section and it was not possible to disaggregate the estimates. A second major change was the adoption of a new approach to estimate forest soil C, the largest C stock in the

United States. For detailed discussion of these new approaches please refer to the Methodology section, Annex 3.13, Domke et al. (in prep), and Woodall et al. (2015). In addition to these major changes, the refined land representation analysis described in Section 6.1 Representation of the U.S. Land Base which identifies some of the forest land in south central and southeastern coastal Alaska as unmanaged; this is in contrast to past assumptions of “managed” land for these forest lands included in the FIA database. Therefore, the C stock and flux estimates for southeast and south central coastal Alaska, as included here, reflect that adjustment, which effectively reduces the managed forest area by approximately 5 percent.

In addition to the creation of explicit estimates of removals and emissions by *Forest Land Remaining Forest Land* versus *Land Converted to Forest Land*, the accounting framework used this year eliminated the use of periodic data (which may be inconsistent with annual inventory data) which contributed to a data artifact in prior estimates of emissions/removals from 1990 to the present. In the previous Inventory report, there was a reduction in net sequestration from 1995 to 2000 followed by an increase in net sequestration from 2000 to 2004. This artifact of comparing inconsistent inventories of the 1980s through 1990s to the nationally consistent inventories of the 2000s has been removed in this Inventory. Overall, there were net C additions to HWP in use and in SWDS combined due, in large part, to updated data on products in use from 2010 to the present. All these changes resulted in an average annual increase in sequestration of 8.9 MMT CO₂ Eq. relative to the previous Inventory.

- *Substitution of Ozone Depleting Substances (HFCs)*. For the current Inventory, reviews of the large retail food and refrigerated transport end-uses resulted in revisions to the Vintaging Model since the previous Inventory report. In addition, a vending machine end-use was added to the Vintaging Model since the previous Inventory. Methodological recalculations were applied to the entire time-series to ensure time-series consistency from 1990 through 2014. For the large retail food end-use, assumptions regarding new installations by system type and refrigerant transitions were revised based on a review of data collected by EPA's GreenChill Partnership and the California Air Resources Board's Refrigerant Management Program. Based on a literature review of technical reports and relevant datasets, the refrigerated transport end-use was updated from an aggregate end-use that covered all the various refrigerated transport modes through average assumptions of charge size, leak rates, stock, and lifetimes to separate end-uses by mode, including road transport, intermodal containers, merchant fishing, reefer ships, and vintage and modern rail. The vending machine end-use was added based on a review of technical reports and sales data. Combined, these assumption changes and additions decreased CO₂-equivalent greenhouse gas emissions on average by 5 percent between 1990 and 2014. Overall, these changes resulted in an average annual decrease in emissions of 6.3 MMT CO₂ Eq. relative to the previous Inventory.
- *Grassland Remaining Grassland - Changes in Agricultural Carbon Stock (CO₂ sink)*. Methodological recalculations in the current Inventory are associated with the following improvements, including (1) incorporation of updated NRI data for 1990 through 2010; (2) inclusion of federal grasslands in the Tier 2 analysis; and (3) improving the simulation of hydric soils in DAYCENT. These changes in soil organic carbon (SOC) stocks resulted in an average annual increase in sequestration of 4.9 MMT CO₂ Eq. relative to the previous Inventory.

Table 9-1: Revisions to U.S. Greenhouse Gas Emissions (MMT CO₂ Eq.)

Gas/Source	1990	2005	2010	2011	2012	2013	Average Annual Change
CO₂	(8.6)	(11.2)	(15.8)	(9.4)	(9.1)	(2.6)	(10.2)
Fossil Fuel Combustion	+ NC	(0.5) NC	(8.9) NC	(3.7) NC	(1.3) NC	(0.1) (1.6)	(1.1) (0.1)
<i>Electricity Generation</i>							
<i>Transportation</i>		(0.8)	(3.7)	(3.9)	(4.0)	(5.4)	(1.5)
<i>Industrial</i>	+ NC	0.2	(0.1)	(0.8)	(1.3)	(5.0)	(0.2)
<i>Residential</i>	NC	+	(0.1)	(0.4)	(0.6)	0.1	+
<i>Commercial</i>	NC	+	(0.1)	(0.3)	(0.4)	0.3	+
<i>U.S. Territories</i>	NC	NC	(4.8)	1.7	5.0	11.6	0.6
Non-Energy Use of Fuels	0.5	+	(0.5)	0.2	0.7	1.8	0.1
Natural Gas Systems	0.1	0.1	0.1	0.1	0.4	0.6	0.1
Cement Production	NC	NC	NC	NC	NC	+	+
Lime Production	+ NC	+	+	+	+	+	+
Other Process Uses of Carbonates	NC	NC	NC	NC	NC	6.0	0.2
Glass Production	NC	NC	NC	NC	NC	0.2	+
Soda Ash Production and Consumption	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Carbon Dioxide Consumption	NC	NC	3.2	3.3	3.2	3.3	0.5
Incineration of Waste	NC	NC	NC	NC	+	(0.7)	+
Titanium Dioxide Production	NC	NC	NC	NC	NC	0.1	+
Aluminum Production	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	(0.2)	+
Urea Consumption for Non-Agricultural Purposes	NC	NC	NC	NC	NC	(0.5)	+
Phosphoric Acid Production	(0.1)	(0.1)	+	+	+	(0.1)	(0.1)
Petrochemical Production	+ (0.7)	(0.1)	(0.1)	+	(0.1)	(0.1)	(0.2)
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	+	+
Lead Production	NC	NC	NC	NC	NC	+	+
Zinc Production	NC	NC	NC	NC	NC	NC	NC
Petroleum Systems	(0.9)	(1.0)	+	(0.3)	(1.2)	(2.3)	(0.9)
Magnesium Production and Processing	+	+	+	NC	NC	+	+
<i>Biomass – Wood^a</i>	NC	NC	NC	NC	NC	3.0	0.1
<i>International Bunker Fuels^a</i>	NC	NC	NC	NC	NC	NC	NC
<i>Biomass – Ethanol^a</i>	NC	NC	NC	NC	NC	NC	NC
CH₄^b	28.4	9.5	55.2	56.5	66.8	85.2	21.3
Stationary Combustion	+	+	+	+	+	+	+
Mobile Combustion	+	(0.3)	+	+	+	+	(0.1)
Coal Mining	NC	NC	NC	NC	NC	NC	NC
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	NC	NC
Natural Gas Systems	27.6	1.0	6.6	10.8	18.2	18.2	12.9
Petroleum Systems	7.2	25.4	32.7	34.3	35.1	39.5	20.7
Petrochemical Production	+	(0.1)	+	+	+	+	+
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC	NC
Iron and Steel Production & Metallurgical Coke Production	(1.1)	(0.8)	(0.6)	(0.7)	(0.7)	(0.7)	(0.9)
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	NC	NC	0.2	0.2	0.4	0.9	0.1
Manure Management	NC	NC	+	0.1	+	+	+
Rice Cultivation	4.0	4.1	0.8	3.4	2.6	3.6	2.7
Field Burning of Agricultural Residues	(0.1)	+	+	+	+	+	+
Landfills	(6.7)	(11.5)	20.3	23.1	27.0	29.7	(6.4)

Wastewater Treatment	+	+	+	+	(0.1)	(0.2)	+
Composting	NC	NC	NC	NC	NC	0.1	+
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
<i>International Bunker Fuels^a</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>
N₂O^b	76.3	41.7	50.3	44.6	43.7	48.2	51.4
Stationary Combustion	+	+	+	+	+	+	+
Mobile Combustion	+	(3.7)	(0.1)	(0.1)	(0.2)	(0.2)	(1.4)
Adipic Acid Production	NC	NC	NC	NC	NC	NC	NC
Nitric Acid Production	+	+	+	+	+	NC	+
Manure Management	0.2	0.1	0.1	0.1	0.2	0.2	0.1
Agricultural Soil Management	79.3	53.5	56.4	57.3	57.1	54.9	60.1
Field Burning of Agricultural Residues	+	+	+	+	+	+	+
Wastewater Treatment	NC	+	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
N ₂ O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	NC	NC	NC	NC	NC
Composting	NC	NC	NC	NC	NC	0.1	+
Semiconductor Manufacture	NC	NC	NC	+	+	+	+
<i>International Bunker Fuels^a</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>	<i>NC</i>
HFCs	NC	(11.4)	(3.1)	(3.0)	(3.5)	(3.7)	(6.3)
Substitution of Ozone Depleting Substances	NC	(11.4)	(3.2)	(3.1)	(3.4)	(4.0)	(6.3)
HCFC-22 Production	NC	NC	(3.2)	(3.1)	(3.4)	(4.0)	(6.3)
Semiconductor Manufacture	NC	+	NC	NC	NC	NC	NC
Magnesium Production and Processing	NC	NC	+	+	+	+	+
PFCs	NC	+	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	0.1	0.1	+	+	+
Semiconductor Manufacture	NC	+	NC	NC	NC	NC	NC
SF₆	NC	+	0.1	0.1	+	+	+
Electrical Transmission and Distribution	NC	+	+	+	(0.1)	0.3	+
Semiconductor Manufacture	NC	+	+	+	(0.1)	0.3	+
Magnesium Production and Processing	NC	NC	+	+	+	+	+
NF₃	NC	+	NC	NC	NC	+	+
Semiconductor Manufacture	NC	+	+	+	+	+	+
Net Change in Total Emissions^b	96.1	28.6	86.6	88.8	97.9	127.0	
Percent Change	1.5%	0.4%	1.3%	1.3%	1.5%	1.9%	

Note: Net change in total emissions presented without LULUCF.

NC - No Change

+ Absolute value does not exceed 0.05 MMT CO₂ Eq. or 0.05 percent.

^a Not included in emissions total.

^b Totals effect of recalculations is underestimated because the 1990 through 2013 Inventory included emissions from LULUCF in totals.

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

Table 9-2: Revisions to Total Net Flux from Land Use, Land-Use Change, and Forestry (MMT CO₂ Eq.)

Land Use Category	1990	2005	2010	2011	2012	2013	Average Annual Change
Forest Land Remaining Forest Land	(82.8)	117.9	20.9	23.9	29.6	39.1	(11.4)
Changes in Forest Carbon Stock ^a	(84.1)	115.2	23.4	37.2	37.3	36.6	(8.9)
Non-CO ₂ Emissions from Forest Fires	1.3	2.7	(2.5)	(13.2)	(7.7)	2.5	(2.6)
N ₂ O Fluxes from Forest Soils ^b	NC	NC	NC	NC	NC	NC	NC
Land Converted to Forest Land	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Changes in Forest Carbon Stock	NC*	NC*	NC*	NC*	NC*	NC*	NC*
Cropland Remaining Cropland	30.9	13.9	27.7	13.3	14.0	12.5	16.5
Changes in Agricultural Carbon Stock ^c	30.9	13.9	27.7	13.3	13.8	14.2	16.5
CO ₂ Emissions from Liming	NC	NC	NC	+	0.2	(2.0)	(0.1)
CO ₂ Emissions from Urea Fertilization	NC	NC	NC	NC	NC	0.3	+
Land Converted to Cropland	41.2	12.3	7.5	5.4	6.0	6.0	21.8
Changes in Agricultural Carbon Stock ^c	41.2	12.3	7.5	5.4	6.0	6.0	21.8
Grassland Remaining Grassland	(11.0)	(7.5)	(19.0)	(8.6)	(8.0)	(8.3)	(4.9)
Changes in Agricultural Carbon Stock ^c	(11.0)	(7.5)	(19.0)	(8.6)	(8.0)	(8.3)	(4.9)
Land Converted to Grassland	46.5	52.1	48.2	48.7	49.1	49.1	49.0
Changes in Agricultural Carbon Stock ^c	46.5	52.1	48.2	48.7	49.1	49.1	49.0
Wetlands Remaining Wetlands	NC	NC	NC	NC	NC	NC	NC
Peatlands Remaining Peatlands	NC	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	NC	+	+	+	+	+	+
Changes in Carbon Stocks in Urban Trees	NC	NC	NC	NC	NC	NC	NC
N ₂ O Fluxes from Settlement Soils ^d	NC	+	+	+	+	+	+
Other	NC	NC	+	0.5	0.5	0.9	0.1
Landfilled Yard Trimmings and Food Scraps	NC	NC	+	0.5	0.5	0.9	0.1
LULUCF Emissions^e	1.3	2.7	(2.5)	(13.2)	(7.4)	0.8	
Net Change in LULUCF Total Net Flux^f	22.8	185.2	87.3	96.1	98.4	98.1	
LULUCF Sector Total^g	24.1	187.9	84.9	82.9	90.9	98.9	
Percent Change	3.2%	21.2%	10.0%	9.8%	10.8%	11.5%	

NC - No Change

+ Absolute value does not exceed 0.05 MMT CO₂ Eq. or 0.05 percent.

* Indicates a new source for the current Inventory year

^a Includes the effects of net additions to stocks of carbon stored in forest ecosystem pools and harvested wood products.

^b Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, but not from land-use conversion.

^c Estimates include C stock changes in all pools.

^d Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.

^e LULUCF emissions include the CO₂, CH₄, and N₂O emissions reported for Non-CO₂ Emissions from Forest Fires, N₂O Fluxes from Forest Soils, CO₂ Emissions from Liming, CO₂ Emissions from Urea Fertilization, Peatlands Remaining Peatlands, and N₂O Fluxes from Settlement Soils.

^f LULUCF Total Net Flux includes any C sequestration gains and losses from all land use and land use conversion categories.

^g The LULUCF Sector Total is the net sum of all emissions (i.e., sources) of greenhouse gases to the atmosphere plus removals of CO₂ (i.e., sinks or negative emissions) from the atmosphere.

Notes: Numbers in parentheses indicate an increase in C sequestration. Totals may not sum due to independent rounding.

10. References

Executive Summary

BEA (2016) *2015 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2015*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: <<http://www.bea.gov/national/index.htm#gdp>>.

Carbon Dioxide Information Analysis Center (CDIAC) (2015) Recent Greenhouse Gas Concentrations. August 2015. Available online at: <http://cdiac.ornl.gov/pns/current_ghg>.

EIA (2016) *Electricity Generation. Monthly Energy Review, February 2016*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2016/02).

EIA (2015) *Electricity in the United States. Electricity Explained*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.

EIA (2013) *International Energy Statistics 2013*. Energy Information Administration (EIA), U.S. Department of Energy. Washington, D.C. Available online at: <<http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>>. 30 November 2014.

EPA (2015a) 1970-2014 Average annual emissions, all criteria pollutants in MS Excel. National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. Last Modified March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

EPA (2015b) Advancing Sustainable Materials Management: Facts and Figures 2013. June 2015. Available online at: <http://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf>.

IEA (2015) *CO₂ Emissions from Fossil Fuel Combustion – Highlights*. International Energy Agency. Available online at: <<https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015.pdf>>.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K., Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*. [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC (1996) *Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change*. [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

NOAA/ESRL (2016) *Trends in Atmospheric Carbon Dioxide*. Available online at: <<http://www.esrl.noaa.gov/gmd/ccgg/trends/>>. 5 February 2016.

UNFCCC (2014) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

U.S. Census Bureau (2015) U.S. Census Bureau International Database (IDB). Available online at: <<http://www.census.gov/ipc/www/idbnew.html>>.

Introduction

Carbon Dioxide Information Analysis Center (CDIAC) (2015) Recent Greenhouse Gas Concentrations. August 2015. Available online at: <http://cdiac.ornl.gov/pns/current_ghg>.

EPA (2009) Technical Support Document for the Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act. U.S. Environmental Protection Agency. December 2009.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*. [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC (1999) Aviation and the Global Atmosphere. Intergovernmental Panel on Climate Change. [J.E. Penner, et al. (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

IPCC/TEAP (2005) *Special Report: Safeguarding the Ozone Layer and the Global Climate System, Chapter 4: Refrigeration*. 2005. Available online at: <<http://www.autos.com/hcfc/technology%20option/Refrigeration/transport%20refrigeration.pdf>>.

Jacobson, M.Z. (2001) "Strong Radiative Heating Due to the Mixing State of Black Carbon in Atmospheric Aerosols." *Nature*, 409:695-697.

NOAA (2014) Vital Signs of the Planet. Available online at: <<http://climate.nasa.gov/causes/>>. Accessed on 12 December 2014.

NOAA/ESRL (2016) *Trends in Atmospheric Carbon Dioxide*. Available online at: <<http://www.esrl.noaa.gov/gmd/ccgg/trends/>>. 5 February 2016.

UNEP/WMO (1999) Information Unit on Climate Change. Framework Convention on Climate Change. Available online at: <<http://unfccc.int>>.

UNFCCC (2014) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013.* (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

Trends in Greenhouse Gas Emissions

BEA (2016) *2015 Comprehensive Revision of the National Income and Product Accounts: Current-dollar and "real" GDP, 1929–2015.* Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. Available online at: <<http://www.bea.gov/national/index.htm#gdp>>.

Duffield, J. (2006) Personal communication. Jim Duffield, Office of Energy Policy and New Uses, U.S. Department of Agriculture, and Lauren Flinn, ICF International. December 2006.

EIA (2016) *Monthly Energy Review, February 2016.* Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2016/02).

EPA (2015a) *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2014.* Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <<http://www.epa.gov/otaq/fetrends-complete.htm>>.

EPA (2015b) 1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel. National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

FRB (2015) *Industrial Production and Capacity Utilization.* Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at: <http://www.federalreserve.gov/releases/G17/table1_2.htm>. July 21, 2015.

IEA (2015) *CO₂ Emissions from Fossil Fuel Combustion – Highlights.* International Energy Agency. Available online at: <<https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015.pdf>>.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change.* [J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

U.S. Census Bureau (2015) U.S. Census Bureau International Database (IDB). Available online at: <<http://www.census.gov/ipc/www/idbnew.html>>.

Energy

IEA (2015) *CO₂ Emissions from Fossil Fuel Combustion – Highlights.* International Energy Agency. Available online at: <<https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2015.pdf>>.

Carbon Dioxide Emissions from Fossil Fuel Combustion

AAR (2008 through 2015) *Railroad Facts.* Policy and Economics Department, Association of American Railroads, Washington, D.C. Obtained from Clyde Crimmel at AAR.

- AISI (2004 through 2013) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.
- APTA (2007 through 2015) *Public Transportation Fact Book*. American Public Transportation Association, Washington, D.C. Available online at: <<http://www.apta.com/resources/statistics/Pages/transitstats.aspx>>.
- APTA (2006) *Commuter Rail National Totals*. American Public Transportation Association, Washington, D.C. Available online at: <<http://www.apta.com/research/stats/rail/crsum.cfm>>.
- BEA (2016) *Table 1.1.6. Real Gross Domestic Product, Chained 2009 Dollars*. Bureau of Economic Analysis (BEA), U.S. Department of Commerce, Washington, D.C. February 2016. Available online at: <<http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=3&isuri=1&904=1990&903=6&906=a&905=2013&910=x&911=0>>.
- Benson, D. (2002 through 2004) Unpublished data. Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.
- Coffeyville Resources Nitrogen Fertilizers (2014) *Nitrogen Fertilizer Operations*. Available online at: <<http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>>.
- Dakota Gasification Company (2006) *CO₂ Pipeline Route and Designation Information*. Bismarck, ND. Available online at: <http://www.dakotagas.com/SafetyHealth/Pipeline_Information.html>.
- DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.
- DLA Energy (2015) Unpublished data from the Fuels Automated System (FAS). Defense Logistics Agency Energy, U.S. Department of Defense. Washington, D.C.
- DOC (1991 through 2015) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.
- DOE (1993 through 2015) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978.
- DOE (2012) *2010 Worldwide Gasification Database*. National Energy Technology Laboratory and Gasification Technologies Council. Available online at: <<http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html>>. Accessed on 15 March 2012.
- DOT (1991 through 2015) *Airline Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. <http://www.transtats.bts.gov/fuel.asp>.
- Eastman Gasification Services Company (2011) Project Data on Eastman Chemical Company's Chemicals-from-Coal Complex in Kingsport, TN. Available online at: <<http://www.netl.doe.gov/coal/gasification/pubs/pdf/Eastman%20Chemicals%20from%20Coal%20Complex.pdf>>.
- EIA (2016) *Monthly Energy Review, February 2016*, Energy Information Administration, U.S. Department of Energy, Washington, DC. DOE/EIA-0035(2016/02).
- EIA (2015a) Electricity in the United States. *Electricity Explained*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: <http://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states>.
- EIA (2015b) *Natural Gas Annual 2014*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(06).
- EIA (2015c) *Quarterly Coal Report: January – March 2015*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.
- EIA (2015d) *U.S. Energy-Related Carbon Dioxide Emissions, 2013*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. October 2014. Available online at: <<http://www.eia.gov/environment/emissions/carbon/>>.
- EIA (1991 through 2015) *Fuel Oil and Kerosene Sales*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <<http://www.eia.gov/petroleum/fueloilkerosene/>>.

EIA (2014) Indicators: CO₂ Emissions. *International Energy Statistics 2014*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <<http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm>>.

EIA (2013) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <<http://www.eia.doe.gov/fuelalternate.html>>.

EIA (2009a) *Emissions of Greenhouse Gases in the United States 2008, Draft Report*. Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE-EIA-0573(2009).

EIA (2009b) *Manufacturing Consumption of Energy 2006*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Released July, 2009.

EIA (2008) *Historical Natural Gas Annual, 1930 – 2008*. Energy Information Administration, U.S. Department of Energy. Washington, D.C.

EIA (2007) Personal Communication. Joel Lou, Energy Information Administration. and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.

EIA (2001) *U.S. Coal, Domestic and International Issues*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. March 2001.

EPA (2015a) Acid Rain Program Dataset 1996-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2015b) Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2015. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <<http://www.epa.gov/otaq/fetrends-complete.htm>>.

EPA (2015c) *Motor Vehicle Emissions Simulator (Moves) 2014a*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <<http://www.epa.gov/otaq/models/moves/index.htm>>.

EPA (2010a) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Erickson, T. (2003) *Plains CO₂ Reduction (PCOR) Partnership*. Presented at the Regional Carbon Sequestration Partnership Meeting Pittsburgh, Pennsylvania, Energy and Environmental Research Center, University of North Dakota. November 3, 2003. Available online at: <<http://www.netl.doe.gov/publications/proceedings/03/carbon-seq/Erickson.pdf>>.

FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.

FHWA (1996 through 2015) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: <<http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm>>.

Fitzpatrick, E. (2002) *The Weyburn Project: A Model for International Collaboration*. Available online at: <<http://www.netl.doe.gov/coalpower/sequestration/pubs/mediarelease/mr-101102.pdf>>.

FRB (2015) *Industrial Production and Capacity Utilization*. Federal Reserve Statistical Release, G.17, Federal Reserve Board. Available online at: <http://www.federalreserve.gov/releases/G17/table1_2.htm>.

Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jacobs, G. (2010) Personal communication. Gwendolyn Jacobs, Energy Information Administration and Rubaab Bhangu, ICF International. *U.S. Territories Fossil Fuel Consumption, 1990–2013*. Unpublished. U.S. Energy Information Administration. Washington, D.C.

Marland, G. and A. Pippin (1990) “United States Emissions of Carbon Dioxide to the Earth’s Atmosphere by Economic Activity.” *Energy Systems and Policy*, 14(4):323.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates. Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

U.S. Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary*. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

USAA (2014) *U.S. Primary Aluminum Production 2013*. U.S. Aluminum Association, Washington, D.C. January, 2014.

USAF (1998) Fuel Logistics Planning. U.S. Air Force: AFPAM23-221. May 1, 1998.

United States Geological Survey (USGS) (1994 through 2011) *Minerals Yearbook: Lead Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2011) *Minerals Yearbook: Manufactured Abrasives Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2011) *2010 Mineral Yearbook; Aluminum [Advanced Release]*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010a) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1991 through 2010b) *Mineral Yearbook: Titanium Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2010) *2009 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2009) *2008 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2007) *2006 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (1995, 1998, 2000 through 2002) *Mineral Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail Energy Consumption, American Short Line and Regional Railroad Association.

Stationary Combustion (excluding CO₂)

EIA (2016) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, February 2016*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2016/02).

EPA (2015) “1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel.” National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

EPA (2003) E-mail correspondance. Air Pollutant data. Office of Air Pollution to the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jacobs, G. (2010) Personal communication. Gwendolyn Jacobs, Energy Information Administration and Rubaab Bhangu, ICF International. *U.S. Territories Fossil Fuel Consumption, 1990–2009*. Unpublished. U.S. Energy Information Administration. Washington, D.C.

SAIC/EIA (2001) *Monte Carlo Simulations of Uncertainty in U.S. Greenhouse Gas Emission Estimates. Final Report*. Prepared by Science Applications International Corporation (SAIC) for Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy. Washington, D.C. June 22, 2001.

Mobile Combustion (excluding CO₂)

AAR (2008 through 2015) *Railroad Facts*. Policy and Economics Department, Association of American Railroads, Washington, D.C. Obtained from Clyde Crimmel at AAR.

ANL (2006) Argonne National Laboratory (2006) GREET model Version 1.7. June 2006.

ANL (2015) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET_1_2015)*. Argonne National Laboratory. October 2015. Available online at: <<https://greet.es.anl.gov>>.

APTA (2007 through 2015) *Public Transportation Fact Book*. American Public Transportation Association, Washington, D.C. Available online at: <<http://www.apta.com/resources/statistics/Pages/transitstats.aspx>>.

APTA (2006) *Commuter Rail National Totals*. American Public Transportation Association, Washington, D.C. Available online at: <<http://www.apta.com/research/stats/rail/crsum.cfm>>.

Benson, D. (2002 through 2004) Personal communication. Unpublished data developed by the Upper Great Plains Transportation Institute, North Dakota State University and American Short Line & Regional Railroad Association.

BEA (1991 through 2015) Unpublished BE-36 survey data. Bureau of Economic Analysis, U.S. Department of Commerce. Washington, D.C.

Browning, L. (2015) "Methodology for Highway Vehicle Alternative Fuel GHG Estimates". Technical Memo, December 2015.

Browning, L. (2009) Personal communication with Lou Browning, "Suggested New Emission Factors for Marine Vessels.", ICF International.

Browning, L. (2005) Personal communication with Lou Browning, Emission control technologies for diesel highway vehicles specialist, ICF International.

DHS (2008) Email Communication. Elissa Kay, Department of Homeland Security and Joe Aamidor, ICF International. January 11, 2008.

DLA Energy (2015) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (1991 through 2015) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOE (1993 through 2015) *Transportation Energy Data Book*. Office of Transportation Technologies, Center for Transportation Analysis, Energy Division, Oak Ridge National Laboratory. ORNL-6978.

DOT (1991 through 2015) *Airline Fuel Cost and Consumption*. U.S. Department of Transportation, Bureau of Transportation Statistics, Washington, D.C. DAI-10. Available online at: <<http://www.transtats.bts.gov/fuel.asp>>.

EDTA (2015) *Electric Drive Sales Dashboard*. Electric Drive Transportation Association, Washington, D.C. Available at: <<http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952>>.

EIA (2016) *Monthly Energy Review, February 2016*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2016/02).

EIA (1991 through 2015) *Fuel Oil and Kerosene Sales*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <http://www.eia.gov/petroleum/fueloilkerosene/>.

EIA (2007 through 2015) *Natural Gas Annual*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0131(11).

EIA (2011) *Annual Energy Review 2010*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0384(2011). October 19, 2011.

- EIA (2015) "Table 3.1: World Petroleum Supply and Disposition." *International Energy Annual*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. Available online at: <<https://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=66&aid=13>>.
- EIA (2007) Personal Communication. Joel Lou, Energy Information Administration and Aaron Beaudette, ICF International. *Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island*. October 24, 2007.
- EIA (2002) *Alternative Fuels Data Tables*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available online at: <<http://www.eia.doe.gov/fuelrenewable.html>>.
- EPA (2015b) *Motor Vehicle Emissions Simulator (Moves) 2014*. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <<http://www.epa.gov/otaq/models/moves/index.htm>>.
- EPA (2015c) Annual Certification Test Results Report. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. Available online at: <<http://www.epa.gov/otaq/crttst.htm>>.
- EPA (2015d) Confidential Engine Family Sales Data Submitted To EPA By Manufacturers. Office of Transportation and Air Quality, U.S. Environmental Protection Agency.
- EPA (2015) "1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.
- EPA (2000) *Mobile6 Vehicle Emission Modeling Software*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.
- EPA (1999a) *Emission Facts: The History of Reducing Tailpipe Emissions*. Office of Mobile Sources. May 1999. EPA 420-F-99-017. Available online at: <<http://www.epa.gov/oms/consumer/f99017.pdf>>.
- EPA (1999b) Regulatory Announcement: EPA's Program for Cleaner Vehicles and Cleaner Gasoline. Office of Mobile Sources. December 1999. EPA420-F-99-051. Available online at: <<http://www.epa.gov/otaq/regs/ld-hwy/tier-2/frm/f99051.pdf>>.
- EPA (1998) *Emissions of Nitrous Oxide from Highway Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–1996*. Office of Mobile Sources, Assessment and Modeling Division, U.S. Environmental Protection Agency. August 1998. EPA420-R-98-009.
- EPA (1997) *Mobile Source Emission Factor Model (MOBILE5a)*. Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor, Michigan.
- EPA (1994a) *Automobile Emissions: An Overview*. Office of Mobile Sources. August 1994. EPA 400-F-92-007. Available online at: <<http://www.epa.gov/otaq/consumer/05-autos.pdf>>.
- EPA (1994b) *Milestones in Auto Emissions Control*. Office of Mobile Sources. August 1994. EPA 400-F-92-014. Available online at: <<http://www.epa.gov/otaq/consumer/12-miles.pdf>>.
- EPA (1993) *Automobiles and Carbon Monoxide*. Office of Mobile Sources. January 1993. EPA 400-F-92-005. Available online at: <<http://www.epa.gov/otaq/consumer/03-co.pdf>>.
- Esser, C. (2003 through 2004) Personal Communication with Charles Esser, Residual and Distillate Fuel Oil Consumption for Vessel Bunkering (Both International and Domestic) for American Samoa, U.S. Pacific Islands, and Wake Island.
- FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.
- FHWA (1996 through 2015) *Highway Statistics*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. Report FHWA-PL-96-023-annual. Available online at: <<http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.htm>>.
- Gaffney, J. (2007) Email Communication. John Gaffney, American Public Transportation Association and Joe Aamidor, ICF International. December 17, 2007.

ICF (2006a) *Revised Gasoline Vehicle EFs for LEV and Tier 2 Emission Levels*. Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2006b) *Revisions to Alternative Fuel Vehicle (AFV) Emission Factors for the U.S. Greenhouse Gas Inventory*. Memorandum from ICF International to John Davies, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. November 2006.

ICF (2004) *Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles*. Final Report to U.S. Environmental Protection Agency. February 2004.

Lipman, T. and M. Delucchi (2002) "Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles." *Climate Change*, 53:477-516.

Santoni, G., B. Lee, E. Wood, S. Herndon, R. Miake-Lye, S Wofsy, J. McManus, D. Nelson, M. Zahniser (2011) Aircraft emissions of methane and nitrous oxide during the alternative aviation fuel experiment. *Environ Sci Technol*. 2011 Aug 15; 45(16):7075-82.

U.S. Census Bureau (2000) *Vehicle Inventory and Use Survey*. U.S. Census Bureau, Washington, D.C. Database CD-EC97-VIUS.

Whorton, D. (2006 through 2014) Personal communication, Class II and III Rail energy consumption, American Short Line and Regional Railroad Association.

Carbon Emitted from Non-Energy Uses of Fossil Fuels

ACC (2015a) "PIPS Year-End Resin Statistics for 2014 vs. 2013: Production, Sales and Captive Use." Available online at: <<http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>>.

ACC (2015b) "Guide to the Business of Chemistry, 2015," American Chemistry Council.

ACC (2014) "U.S. Resin Production & Sales: 2013 vs. 2012," American Chemistry Council. Available online at: <<http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>>.

ACC (2012) "Guide to the Business of Chemistry, 2012," American Chemistry Council.

ACC (2003-2011) "PIPS Year-End Resin Statistics for 2010: Production, Sales and Captive Use." Available online at: <<http://www.americanchemistry.com/Jobs/EconomicStatistics/Plastics-Statistics/Production-and-Sales-Data-by-Resin.pdf>>.

Bank of Canada (2014) Financial Markets Department Year Average of Exchange Rates. Available online at: <<http://www.bankofcanada.ca/stats/assets/pdf/nraa-2013.pdf>>.

Bank of Canada (2013) Financial Markets Department Year Average of Exchange Rates. Available online at: <<http://www.bankofcanada.ca/stats/assets/pdf/nraa-2012.pdf>>.

Bank of Canada (2012) Financial Markets Department Year Average of Exchange Rates. Available online at: <<http://www.bankofcanada.ca/stats/assets/pdf/nraa-2011.pdf>>.

EIA (2015a) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2015*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (2015b) Supplemental Tables on Petroleum Product detail. *Monthly Energy Review, December 2015*. Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (2013) *EIA Manufacturing Consumption of Energy (MECS) 2010*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2010) *EIA Manufacturing Consumption of Energy (MECS) 2006*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2005) *EIA Manufacturing Consumption of Energy (MECS) 2002*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (2001) *EIA Manufacturing Consumption of Energy (MECS) 1998*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1997) *EIA Manufacturing Consumption of Energy (MECS) 1994*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EIA (1994) *EIA Manufacturing Consumption of Energy (MECS) 1991*. U.S. Department of Energy, Energy Information Administration, Washington, D.C.

EPA (2015a) “1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel.” National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

EPA (2015b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2014a) Municipal Solid Waste in the United States: 2012 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <<http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>>.

EPA (2014b) Chemical Data Access Tool (CDAT). U.S. Environmental Protection Agency, June 2014. Available online at: <http://java.epa.gov/oppt_chemical_search/>. Accessed January 2015.

EPA (2013a) Municipal Solid Waste in the United States: 2011 Facts and Figures. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <<http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm>>.

EPA (2013b) *Resource Conservation and Recovery Act (RCRA) Info*, Biennial Report, GM Form (Section 2- Onsite Management) and WR Form.

EPA (2011) EPA's Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates. Available online at: <<http://www.epa.gov/oppbead1/pestsales/>>. Accessed January 2012.

EPA (2009) Biennial Reporting System (BRS) Database. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: <<http://www.epa.gov/enviro/html/brs/>>. Data for 2001-2007 are current as of Sept. 9, 2009.

EPA (2004) EPA's Pesticides Industry Sales and Usage, 2000 and 2001 Market Estimates. Available online at: <<http://www.epa.gov/oppbead1/pestsales/>>. Accessed September 2006.

EPA (2002) EPA's Pesticides Industry Sales and Usage, 1998 and 1999 Market Estimates, table 3.6. Available online at: <http://www.epa.gov/oppbead1/pestsales/99pestsales/market_estimates1999.pdf>. Accessed July 2003.

EPA (2001) AP 42, Volume I, Fifth Edition. Chapter 11: Mineral Products Industry. Available online at: <<http://www.epa.gov/ttn/chief/ap42/ch11/index.html>>.

EPA (2000a) *Biennial Reporting System (BRS)*. U.S. Environmental Protection Agency, Envirofacts Warehouse. Washington, D.C. Available online at: <<http://www.epa.gov/enviro/html/brs/>>.

EPA (2000b) *Toxics Release Inventory, 1998*. U.S. Environmental Protection Agency, Office of Environmental Information, Office of Information Analysis and Access, Washington, D.C. Available online at: <<http://www.epa.gov/triexplorer/chemical.htm>>.

EPA (1999) EPA's Pesticides Industry Sales and Usage, 1996-1997 Market Estimates. Available online at: <http://www.epa.gov/oppbead1/pestsales/97pestsales/market_estimates1997.pdf>.

EPA (1998) EPA's Pesticides Industry Sales and Usage, 1994-1995 Market Estimates. Available online at: <http://www.epa.gov/oppbead1/pestsales/95pestsales/market_estimates1995.pdf>.

FEB (2013) Fiber Economics Bureau, as cited in C&EN (2013) Lackluster Year for Chemical Output: Production stayed flat or dipped in most world regions in 2012. Chemical &Engineering News, American Chemical Society, 1 July. Available online at: <<http://www.cen-online.org>>.

FEB (2012) Fiber Economics Bureau, as cited in C&EN (2012) Too Quiet After the Storm: After a rebound in 2010, chemical production hardly grew in 2011. Chemical & Engineering News, American Chemical Society, 2 July. Available online at: <<http://www.cen-online.org>>.

FEB (2011) Fiber Economics Bureau, as cited in C&EN (2011) *Output Ramps up in all Regions*. Chemical Engineering News, American Chemical Society, 4 July. Available online at: <<http://www.cen-online.org>>.

FEB (2010) Fiber Economics Bureau, as cited in C&EN (2010) *Output Declines in U.S., Europe*. Chemical & Engineering News, American Chemical Society, 6 July. Available online at: <<http://www.cen-online.org>>.

FEB (2009) Fiber Economics Bureau, as cited in C&EN (2009) *Chemical Output Slipped In Most Regions* Chemical & Engineering News, American Chemical Society, 6 July. Available online at: <<http://www.cen-online.org>>.

FEB (2007) Fiber Economics Bureau, as cited in C&EN (2007) *Gains in Chemical Output Continue*. Chemical & Engineering News, American Chemical Society. July 2, 2007. Available online at: <<http://www.cen-online.org>>.

FEB (2005) Fiber Economics Bureau, as cited in C&EN (2005) *Production: Growth in Most Regions* Chemical & Engineering News, American Chemical Society, 11 July. Available online at: <<http://www.cen-online.org>>.

FEB (2003) Fiber Economics Bureau, as cited in C&EN (2003) *Production Inches Up in Most Countries*, Chemical & Engineering News, American Chemical Society, 7 July. Available online at: <<http://www.cen-online.org>>.

FEB (2001) Fiber Economics Bureau, as cited in ACS (2001) *Production: slow gains in output of chemicals and products lagged behind U.S. economy as a whole* Chemical & Engineering News, American Chemical Society, 25 June. Available online at: <<http://pubs.acs.org/cen>>.

Financial Planning Association (2006) Canada/US Cross-Border Tools: US/Canada Exchange Rates. Available online at: <http://www.fpanet.org/global/planners/US_Canada_ex_rates.cfm>. Accessed on August 16, 2006.

Gosselin, Smith, and Hodge (1984) "Clinical Toxicology of Commercial Products." Fifth Edition, Williams & Wilkins, Baltimore.

Huurman, J.W.F. (2006) *Recalculation of Dutch Stationary Greenhouse Gas Emissions Based on Sectoral Energy Statistics 1990-2002*. Statistics Netherlands, Voorburg, The Netherlands.

IISRP (2003) "*IISRP Forecasts Moderate Growth in North America to 2007*" International Institute of Synthetic Rubber Producers, Inc. New Release. Available online at: <<http://www.iisrp.com/press-releases/2003-Press-Releases/IISRP-NA-Forecast-03-07.html>>.

IISRP (2000) "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" International Institute of Synthetic Rubber Producers press release.

INEGI (2006) Producción bruta total de las unidades económicas manufactureras por Subsector, Rama, Subrama y Clase de actividad. Available online at: <http://www.inegi.gob.mx/est/contenidos/espanol/proyectos/censos/ce2004/tb_manufacturas.asp>. Accessed on August 15, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Marland, G., and R.M. Rotty (1984) "Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-1982", Tellus 36b:232-261.

NPRA (2002) North American Wax - A Report Card. Available online at: <<http://www.npra.org/members/publications/papers/lubes/LW-02-126.pdf>>.

RMA (2014) *2013 U.S. Scrap Tire Management Summary*. Rubber Manufacturers Association, Washington, D.C. November 2014.

RMA (2011) *U.S. Scrap Tire Management Summary: 2005-2009*. Rubber Manufacturers Association, Washington, D.C. October 2011, updated September 2013.

- RMA (2009) “Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics.” Rubber Manufacturers Association., Washington D.C. Available online at:
http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/ Accessed on 17 September 2009.
- Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.
- U.S. Bureau of the Census (2015) U.S International Trade Commission (USITC) Trade Dataweb. Available online at: <<http://dataweb.usitc.gov>>.
- U.S. Census Bureau (2014) 2012 Economic Census. Available online at:
http://www.census.gov/econ/census/schedule/whats_been_released.html. Accessed November 2014.
- U.S. Census Bureau (2009) *Soap and Other Detergent Manufacturing: 2007*. Available online at:
http://smppbf1.dsd.census.gov/TheDataWeb_HotReport/servlet/HotReportEngineServlet?emailname=vh@boc&filename=mfg1.hrml&20071204152004.Var.NAICS2002=325611&forward=20071204152004.Var.NAICS2002.
- U.S. Census Bureau (2004) *Soap and Other Detergent Manufacturing: 2002*. Issued December 2004. EC02-31I-325611 (RV). Available online at: <<http://www.census.gov/prod/ec02/ec0231i325611.pdf>>.
- U.S. Census Bureau (1999) *Soap and Other Detergent Manufacturing: 1997*. Available online at:
<http://www.census.gov/epcd/www/ec97stat.htm>.
- U.S. International Trade Commission (1990-2015) “Interactive Tariff and Trade DataWeb: Quick Query.” Available online at: <<http://dataweb.usitc.gov>>. Accessed December 2015.

Incineration of Waste

- ArSova, Ljupka, Rob van Haaren, Nora Goldstein, Scott M. Kaufman, and Nickolas J. Themelis (2008) “16th Annual BioCycle Nationwide Survey: The State of Garbage in America” Biocycle, JG Press, Emmaus, PA. December.
- Bahor, B (2009) Covanta Energy’s public review comments re: *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007*. Submitted via email on April 9, 2009 to Leif Hockstad, U.S. EPA.
- Berenyi, E. B. (2014) “A Compatibility Study: Recycling and Waste-to-Energy Work in Concert”. Governmental Advisory Associates, Inc. Available online at: <http://www.energyrecoverycouncil.org/userfiles/files/2014-Berenyi-recycling-study.pdf>
- De Soete, G.G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, Emissions and Control.” In A. R. Van Amstel, (ed.) Proc. of the International Workshop Methane and Nitrous Oxide: Methods in National Emission Inventories and Options for Control, Amersfoort, NL. February 3-5, 1993.
- Energy Recovery Council (2009) “2007 Directory of Waste-to-Energy Plants in the United States.” Accessed on September 29, 2009.
- EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013 – Assessing Trends in Material Generation, Recycling and Disposal in the United States*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at:
http://www3.epa.gov/epawaste/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf.
- EPA (2007, 2008, 2011, 2013, 2014) *Municipal Solid Waste in the United States: Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. Available online at:
<http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>.
- EPA (2006) *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C.
- EPA (2000) *Characterization of Municipal Solid Waste in the United States: Source Data on the 1999 Update*. Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. EPA530-F-00-024.
- Goldstein, N. and C. Madtes (2001) “13th Annual BioCycle Nationwide Survey: The State of Garbage in America.” BioCycles, JG Press, Emmaus, PA. December 2001.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kaufman, et al. (2004) "14th Annual BioCycle Nationwide Survey: The State of Garbage in America 2004" BioCycle, JG Press, Emmaus, PA. January, 2004.

RMA (2014) "2013 U.S. Scrap Tire Management Summary." Rubber Manufacturers Association. November 2014. Available online at: <http://www.rma.org/download/scrap-tires/market-reports/US_STMarket2013.pdf>.

RMA (2012a) "Rubber FAQs." Rubber Manufacturers Association. Available online at: <<http://www.rma.org/about-rma/rubber-faqs/>>. Accessed on 19 November 2014.

RMA (2012b) "Scrap Tire Markets: Facts and Figures – Scrap Tire Characteristics." Rubber Manufacturers Association. Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/>. Accessed 18 on January 2012.

RMA (2011) "U.S. Scrap Tire Management Summary 2005-2009." Rubber Manufacturers Association. October 2011. Available online at: <http://www.rma.org/scrap_tires/scrap_tire_markets/2009_summary.pdf>.

RTI (2009) Updated Hospital/Medical/Infectious Waste Incinerator (HMIWI) Inventory Database. Memo dated July 6, 2009. Available online at: <http://www.epa.gov/ttnatw01/129/hmiwi/hmiwi_inventory.pdf>.

Schneider, S. (2007) E-mail between Shelly Schneider of Franklin Associates (a division of ERG) and Sarah Shapiro of ICF International, January 10, 2007.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States—A National Survey. Thesis. Columbia University, Department of Earth and Environmental Engineering, January 3, 2014.

Shin and Themelis. (2014) "U.S. Survey of Generation and Disposition of Municipal Solid Waste". January 2016. Available online at: <<http://www.americanchemistry.com/Policy/Energy/Energy-Recovery/2014-Update-of-Potential-for-Energy-Recovery-from-Municipal-Solid-Waste-and-Non-Recycled-Plastics.pdf>>

Simmons, et al. (2006) "15th Nationwide Survey of Municipal Solid Waste Management in the United States: The State of Garbage in America." BioCycle, JG Press, Emmaus, PA. April 2006.

van Haaren, Rob, Themelis, N., and Goldstein, N. (2010) "The State of Garbage in America." BioCycle, October 2010. Volume 51, Number 10, pg. 16-23.

Coal Mining

AAPG (1984) *Coalbed Methane Resources of the United States*. AAPG Studies in Geology Series #17.

CAR (2015) *Project Database*. Climate Action Reserve. Available at <<http://www.climateactionreserve.org/>>.

Creedy, D.P. (1993) Methane Emissions from Coal Related Sources in Britain: Development of a Methodology. *Chemosphere*, 26: 419-439.

EIA (2015) *Annual Coal Report 2014*. Table 1. Energy Information Administration, U.S. Department of Energy.

El Paso (2009) Shoal Creek Mine Plan, El Paso Exploration & Production.

EPA (2015) GHGRP 2015: Underground Coal Mines.

EPA (2005) *Surface Mines Emissions Assessment*. Draft. U.S. Environmental Protection Agency.

EPA (1996) *Evaluation and Analysis of Gas Content and Coal Properties of Major Coal Bearing Regions of the United States*. EPA/600/R-96-065. U.S. Environmental Protection Agency.

GSA (2016) *Well Records Database*. Geological Survey of Alabama State Oil and Gas Board. Available online at <<http://www.gsa.state.al.us/ogb/database.aspx>>.

IEA (2015) *Key World Energy Statistics*. Coal Production, International Energy Agency.

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories*. Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia. Eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M. IGES.

JWR (2010) *No. 4 & 7 Mines General Area Maps*. Walter Energy: Jim Walter Resources.

King, Brian (1994) *Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implication of Options*. Neil and Gunter Ltd.

Mutmansky, Jan M. and Yanbei Wang (2000) Analysis of Potential Errors in Determination of Coal Mine Annual Methane Emissions. *Mineral Resources Engineering*, 9(4).

Saghafi, Abouna (2013) *Estimation of Fugitive Emissions from Open Cut Coal Mining and Measurable Gas Content*. 13th Coal Operators' Conference, University of Wollongong, The Australian Institute of Mining and Metallurgy & Mine Managers Association of Australia. 306-313.

USBM (1986) *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*. Circular 9067. U.S. Bureau of Mines.

WVGES (2015) *Oil & Gas Production Data*. West Virginia Geological & Economic Survey. Available online at <<http://www.wvgs.wvnet.edu/www/datastat/datastat.htm>>.

Abandoned Underground Coal Mines

EPA (2004) *Methane Emissions Estimates & Methodology for Abandoned Coal Mines in the U.S.* Draft Final Report. Washington, D.C. April 2004.

MSHA (2015) U.S. Department of Labor, Mine Health & Safety Administration (2015) *Data Retrieval System*. Available online at: <<http://www.msha.gov/drs/drshome.htm>>.

Petroleum Systems

Allen et al. (2014) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. ES&T. December 9, 2014. Available online at: <<http://pubs.acs.org/doi/pdf/10.1021/es5040156>>.

API (2009) Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Gas Industry. American Petroleum Institute. Austin, TX, August 2009.

BOEM (2011a) *OCS Platform Activity*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at: <http://www.boem.gov/uploadedFiles/BOEM/Newsroom/Offshore_Stats_and_Facts/Gulf_of_Mexico_Region/OCS_PlatformActivity.pdf>.

BOEM (2011b) *Platform Information and Data*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at: <https://www.data.boem.gov/homepg/data_center/platform/platform.asp>.

BOEM (2011c) *Pacific OCS Region*. Bureau of Ocean Energy Management, U.S. Department of Interior. Available online at: <http://www.data.boem.gov/homepg/data_center/platform/PacificFreePlat.asp>.

BOEM (2014) *Year 2011 Gulfwide Emission Inventory Study*. Bureau of Ocean Energy Management, U.S. Department of Interior. OCS Study BOEM 2014-666. Available online at: <<http://www.data.boem.gov/PI/PDFImages/ESPIS/5/5440.pdf>>

DrillingInfo (2015) March 2015 Download. DI Desktop® DrillingInfo, Inc.

EIA (1990 through 2015) *Refinery Capacity Report*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at: <<http://www.eia.gov/petroleum/refinerycapacity/>>.

EIA (1995 through 2015a) *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy. Washington, DC. Available online at: <<http://www.eia.gov/totalenergy/data/monthly/index.cfm>>.

EIA (1995 through 2015b) *Petroleum Supply Annual. Volume 1*. U.S Department of Energy Washington, DC. Available online at: <<http://www.eia.gov/petroleum/supply/annual/volume1/>>.

EPA (2016a) Inventory of U.S. Greenhouse Gas Emissions and Sinks: Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2016b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015a) *Greenhouse Gas Reporting Program*. Environmental Protection Agency. Data reported as of August 16, 2015.

EPA (2015b) Background Technical Support Document for the Proposed New Source Performance Standards 40 CFR Part 60, subpart OOOa. Available online at: <https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2010-0505-5021>

EPA (2015c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platforms Emissions Estimate. Available online at: <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>.

EPA (2015d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Refineries Emissions Estimate. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2005) *Incorporating the Mineral Management Service Gulfwide Offshore Activities Data System (GOADS) 2000 data into the methane emissions inventories*. Prepared by ICF International. U.S. Environmental Protection Agency. 2005.

EPA (1999a) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)*. Prepared by ICF International. Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA (1999b) *Methane Emissions from the U.S. Petroleum Industry*. Prepared by Radian International. U.S. Environmental Protection Agency. February 1999.

EPA/GRI (1996a) *Methane Emissions from the Natural Gas Industry, V7: Blow and Purge Activities*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996b) *Methane Emissions from the Natural Gas Industry, V11: Compressor Driver Exhaust*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996c) *Methane Emissions from the Natural Gas Industry, V12: Pneumatic Devices*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

EPA/GRI (1996d) *Methane Emissions from the Natural Gas Industry, V13: Chemical Injection Pumps*. Prepared by Radian. U.S. Environmental Protection Agency. April 1996.

HPDI (2011) Production and Permit Data, October 2009.

IOGCC (2012) *Marginal Wells: fuel for economic growth 2012 Report*. Interstate Oil & Gas Compact Commission. Available online at: <http://iogcc.ok.gov/Websites/iogcc/images/MarginalWell/MW_2012_report.pdf>.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Pachauri, R.K and Reisinger, A. (eds.)]; IPCC, Geneva, Switzerland.

OGJ (2015) *Oil and Gas Journal 1990-2014. Oil Pipelines*, Vol 113, Issue 9, September 7, 2015.

United States Army Corps of Engineers (1995 through 2015) *Waterborne Commerce of the United States, Part 5: National Summaries*. U.S. Army Corps of Engineers. Washington, DC, July 20, 2015. Available online at: <<http://www.navigationdatacenter.us/wcsc/pdf/wcusnatl13.pdf>>.

Natural Gas Systems

AGA (1991 through 1998) Gas Facts. American Gas Association. Washington, DC.

Alabama (2015) Alabama State Oil and Gas Board. Available online at: <<http://www.ogb.state.al.us>>.

Allen et al. (2014a) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Liquids Unloading. ES&T. December 9, 2014. Available online at: <<http://pubs.acs.org/doi/abs/10.1021/es504016r>>.

Allen et al. (2014b) Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. ES&T. December 9, 2014. Available online at: <<http://pubs.acs.org/doi/pdf/10.1021/es5040156>>.

Allen et al. (2013) Measurements of methane emissions at natural gas production sites in the United States. doi: 10.1073/pnas.1304880110 PNAS September 16, 2013. Available online at: <<http://www.pnas.org/content/early/2013/09/10/1304880110.abstract>>.

API/ANGA (2012) *Characterizing Pivotal Sources of Methane Emissions from Natural Gas Production – Summary and Analysis of API and ANGA Survey Responses*. Final Report. American Petroleum Institute and America's Natural Gas Alliance. September 21.

BOEMRE (2011a) Gulf of Mexico Region Offshore Information. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011b) Pacific OCS Region Offshore Information. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011c) GOM and Pacific OCS Platform Activity. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

BOEMRE (2011d) Pacific OCS Region. Bureau of Ocean Energy Management, Regulation and Enforcement, U.S. Department of Interior.

DrillingInfo (2015) December 2014 Download. DI Desktop® DrillingInfo, Inc.

EIA (2015a) "Table 1— Summary of natural gas supply and disposition in the United States, 2009-2014." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <<http://www.eia.doe.gov>>.

EIA (2015b) "Table 2—Natural Gas Consumption in the United States, 2009-2014." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <<http://www.eia.doe.gov>>.

EIA (2015c) "Table 7 - Marketed production of natural gas in selected states and the Federal Gulf of Mexico, 2009-2014." Natural Gas Monthly, Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <<http://www.eia.doe.gov>>.

EIA (2015d) Number of Natural Gas Consumers – Residential. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN3_Count_a.htm>.

EIA (2015e) Number of Natural Gas Consumers – Commercial. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN5_Count_a.htm>.

EIA (2015f) Number of Natural Gas Consumers – Industrial. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <http://www.eia.gov/dnav/ng/ng_cons_num_a_EPG0_VN7_Count_a.htm>.

EIA (2014d) U.S. Natural Gas Imports by Country. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <<http://www.eia.doe.gov>>.

EIA (2014e) Natural Gas Gross Withdrawals and Production. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <<http://www.eia.doe.gov>>.

EIA (2012a) Formation crosswalk. Energy Information Administration, U.S. Department of Energy, Washington, DC. Provided July 7.

EIA (2012b) Lease Condensate Production, 1979-2012, Natural Gas Navigator. Energy Information Administration, U.S. Department of Energy, Washington, DC. Available online at: <http://www.eia.gov/dnav/ng/ng_prod_lc_s1_a.htm>.

EIA (2005) “Table 5—U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 1977-2003.” Energy Information Administration, Department of Energy, Washington, DC.

EIA (2004) *US LNG Markets and Uses*. Energy Information Administration, U.S. Department of Energy, Washington, DC. June 2004.

EIA (2001) “Documentation of the Oil and Gas Supply Module (OGSM).” Energy Information Administration, U.S. Department of Energy, Washington, DC.

EPA (2016a) Inventory of U.S. Greenhouse Gas Emissions and Sinks: Additional Information and Updates under Consideration for Natural Gas and Petroleum Systems Uncertainty Estimates. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2016b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas and Petroleum Production Emissions. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2016c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Gathering and Boosting Emissions. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2016d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Transmission and Storage Emissions. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2016e) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Distribution Emissions. Available online at: <<https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015a) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Data Source for Well Counts. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015b) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Offshore Oil and Gas Platform Emission Estimates. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015c) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Update to Hydraulically Fractured Gas Well Completions and Workover Estimate. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015d) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Updates to Pneumatic Controller Emissions Estimate. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015e) Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2013: Potential Updates to Liquids Unloading Emissions Estimate. Available online at: <<http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/natural-gas-systems.html>>.

EPA (2015) *Greenhouse Gas Reporting Program- Subpart W – Petroleum and Natural Gas Systems*. Environmental Protection Agency. Data reported as of August 16, 2015.

EPA (2013a) *Oil and Natural Gas Sector: Standards of Performance for Crude Oil and Natural Gas Production, Transmission, and Distribution. Background Supplemental Technical Support Document for the Final New Source Performance Standards*. Environmental Protection Agency. September 2013.

EPA (2013b) *Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews*. Environmental Protection Agency, 40 CFR Parts 60 and 63, [EPA-HQ-OAR-2010-0505; FRL-9665-1], RIN 2060-AP76.

EPA (2013c) Natural Gas STAR Reductions 1990-2012. Natural Gas STAR Program. September 2013.

EPA (2013d) Updating GHG Inventory Estimate for Hydraulically Fractured Gas Well Completions and Workovers. Available online at: <<http://www.epa.gov/climatechange/Downloads/ghgemissions/memo-update-emissions-for-hydraulically-workovers.pdf>>.

EPA (1999) *Estimates of Methane Emissions from the U.S. Oil Industry (Draft Report)*. Prepared by ICF-Kaiser, Office of Air and Radiation, U.S. Environmental Protection Agency. October 1999.

EPA/GRI (1996) *Methane Emissions from the Natural Gas Industry*. Prepared by Harrison, M., T. Shires, J. Wessels, and R. Cowgill, eds., Radian International LLC for National Risk Management Research Laboratory, Air Pollution Prevention and Control Division, Research Triangle Park, NC. EPA-600/R-96-080a.

FERC (2015) *North American LNG Terminals*. Federal Energy Regulatory Commission, Washington, D.C.

GTI (2001) Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. GRI-01/0136.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jackson et al., (2014) *Natural Gas Pipeline Leaks Across Washington, D.C.*, 48 Environ. Science Technology 2051-2058, January 16, 2014. Available online at: <<http://pubs.acs.org/doi/abs/10.1021/es404474x>>. March 24, 2014.

Lamb, et al. (2015) "Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States." *Environmental Science & Technology*, Vol. 49 5161-5169.

Lyon, et al. (2015) "Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region." *Environmental Science & Technology*, Vol. 49 8147-8157.

Marchese, et al. (2015) "Methane Emissions from United States Natural Gas Gathering and Processing." *Environmental Science and Technology*, Vol. 49 10718-10727.

McGeehan et al., (2014) *Beneath Cities, a Decaying Tangle of Gas Pipes*, N.Y. Times, March 24, 2014. Available online at: <http://www.nytimes.com/2014/03/24/nyregion/beneath-cities-a-decaying-tangle-of-gas-pipes.html?hp&_r=0>.

Miller et al. (2013) Anthropogenic emissions of methane in the United States. November 25, 2013, doi: 10.1073/pnas.1314392110. Available online at: <<http://www.pnas.org/content/early/2013/11/20/1314392110.abstract>>.

OGJ (1997-2015) "Worldwide Gas Processing." *Oil & Gas Journal*, PennWell Corporation, Tulsa, OK. Available online at: <<http://www.ogj.com/>>.

Payne, B & Ackley, R., (2013a) "Extended Report and Preliminary Investigation of Ground-Level Ambient Methane Levels in Manhattan, New York, NY". 11 March 2013.

Payne, B. & Ackley, R., (2013b) "Report on a Survey of Ground-Level Ambient Methane Levels in the Vicinity of Wyalusing, Bradford County, PA." November 2013.

Payne, B. & Ackley, R., (2012) "Report to the Clean Air Council on 8 June, 2012 Field Inspection and Methane Sampling Survey of Parts of Leroy, Granville and Franklin Townships, Bradford County, PA." 2012.

Peischl, J. et al., (2013) "Quantifying Sources of Methane Using Light Alkenes in the Los Angeles Basin, CA," *J. Geophys. Res. Atmos.* 118, 4974-4990, doi: 10.1002/jgrd.50413.

Petron, Gabrielle, et al., (2012) Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study, *Journal of Geophysical Research* doi:10.1029/2011JD016360.

Phillips, N.G., et al., (2012) "Mapping Urban Pipeline Leaks: Methane Levels Across Boston," *Environmental Pollution* Available online at: <<http://www.ncbi.nlm.nih.gov/pubmed/23174345>>.

PHMSA (2015a) Transmission Annuals Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: <<http://phmsa.dot.gov/pipeline/library/data-stats>>.

PHMSA (2015b) Gas Distribution Annual Data. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, Washington, DC. Available online at: <<http://phmsa.dot.gov/pipeline/library/data-stats>>.

Wyoming (2015) Wyoming Oil and Gas Conservation Commission. Available online at: <<http://wogcc.state.wy.us/coalbedchart.cfm>>.

Zimmerle, et al. (2015) "Methane Emissions from the Natural Gas Transmission and Storage System in the United States." *Environmental Science and Technology*, Vol. 49 9374–9383.

Energy Sources of Indirect Greenhouse Gases

EPA (2015) "1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

International Bunker Fuels

Anderson, B.E., et al. (2011) *Alternative Aviation Fuel Experiment (AAFEX)*, NASA Technical Memorandum, in press.

ASTM (1989) *Military Specification for Turbine Fuels, Aviation, Kerosene Types*, NATO F-34 (JP-8) and NATO F-35. February 10, 1989. Available online at: <http://test.wbdg.orgccb/FEDMIL/t_83133d.pdf>.

Chevron (2000) *Aviation Fuels Technical Review (FTR-3)*. Chevron Products Company, Chapter 2. Available online at: <http://www.chevron.com/products/prodserv/fuels/bulletin/aviationfuel/2_at_fuel_perf.shtml>.

DHS (2008) Personal Communication with Elissa Kay, Residual and Distillate Fuel Oil Consumption (International Bunker Fuels). Department of Homeland Security, Bunker Report. January 11, 2008.

DLA Energy (2015) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

DOC (2015) Unpublished Report of Bunker Fuel Oil Laden on Vessels Cleared for Foreign Countries. Form-563. Foreign Trade Division, Bureau of the Census, U.S. Department of Commerce. Washington, D.C.

DOT (1991 through 2013) Fuel Cost and Consumption. Federal Aviation Administration, Bureau of Transportation Statistics, U.S. Department of Transportation. Washington, D.C. DAI-10.

EIA (2016) *Monthly Energy Review, February 2016*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2016/02).

FAA (2016) Personal Communication between FAA and Leif Hockstad for aviation emissions estimates from the Aviation Environmental Design Tool (AEDT). February 2016.

FAA (2006) *System for assessing Aviation's Global Emission (SAGE) Model*. Federal Aviation Administration's Office of Aviation Policy, Planning, and Transportation Topics, 2006.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USAF (1998) *Fuel Logistics Planning*. U.S. Air Force pamphlet AFPAM23-221, May 1, 1998.

Wood Biomass and Ethanol Consumption

EIA (2016) *Monthly Energy Review, February 2016*. Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0035(2015/12).

EPA (2015) Acid Rain Program Dataset 1996-2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Lindstrom, P. (2006) Personal Communication. Perry Lindstrom, Energy Information Administration and Jean Kim, ICF International.

Industrial Processes and Product Use

IPCC (2011) *Use of Models and Facility-Level Data in Greenhouse Gas Inventories* (Report of IPCC Expert Meeting on Use of Models and Measurements in Greenhouse Gas Inventories 9-11 August 2010, Sydney, Australia) eds: Eggleston H.S., Srivastava N., Tanabe K., Baasansuren J., Fukuda M., Pub. IGES, Japan 2011.

EPA (2014) *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>.

Cement Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Bureau of Mines (1990 through 1993) *Minerals Yearbook: Cement Annual Report*. U.S. Department of the Interior, Washington, D.C.

United States Geological Survey (USGS) (2015a) *Mineral Industry Survey: Cement in June 2015*. U.S. Geological Survey, Reston, VA. August, 2015.

USGS (2015b) *Mineral Commodity Summaries: Cement 2015*. U.S. Geological Survey, Reston, VA. January, 2015.

USGS (1995 through 2013) *Minerals Yearbook - Cement*. U.S. Geological Survey, Reston, VA.

Van Oss (2013a) 1990 through 2012 Clinker Production Data Provided by Hendrik van Oss (USGS) via email on November 8, 2013.

Van Oss (2013b) Personal communication. Hendrik van Oss, Commodity Specialist of the U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. October 28, 2013.

Lime Production

Corathers (2015) Personal communication, Lisa Corathers, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

EPA (2015) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart S -National Lime Production for Calendar Years 2010 through 2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Males, E. (2003) Memorandum from Eric Males, National Lime Association to Mr. William N. Irving & Mr. Leif Hockstad, Environmental Protection Agency. March 6, 2003.

Miner, R. and B. Upton (2002) Methods for estimating greenhouse gas emissions from lime kilns at kraft pulp mills. Energy. Vol. 27 (2002), p. 729-738.

Seeger (2013) Memorandum from Arline M. Seeger, National Lime Association to Mr. Leif Hockstad, Environmental Protection Agency. March 15, 2013.

United States Geological Survey (USGS) (1992 through 2014) *Minerals Yearbook: Lime*. U.S. Geological Survey, Reston, VA.

Glass Production

EPA (2009) *Technical Support Document for the Glass Manufacturing Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases*. U.S. Environmental Protection Agency, Washington, D.C.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

OIT (2002) *Glass Industry of the Future: Energy and Environmental Profile of the U.S. Glass Industry*. Office of Industrial Technologies, U.S. Department of Energy. Washington, D.C.

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

United States Geological Survey (USGS) (2015a) *Minerals Industry Surveys; Soda Ash in January 2015*. U.S. Geological Survey, Reston, VA. March, 2015.

USGS (1995 through 2015b) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995 through 2014) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

Willett (2015) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 9, 2015.

Willett (2014) Personal communication., Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 25, 2014.

Other Process Uses of Carbonates

U.S. Bureau of Mines (1991 and 1993a) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Department of the Interior. Washington, D.C.

U.S. Bureau of Mines (1990 through 1993b) *Minerals Yearbook: Magnesium and Magnesium Compounds Annual Report*. U.S. Department of the Interior. Washington, D.C.

United States Geological Survey (USGS) (2013a) *Magnesium Metal Mineral Commodity Summary for 2013*. U.S. Geological Survey, Reston, VA.

USGS (1995a through 2015) *Minerals Yearbook: Crushed Stone Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995b through 2012) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA.

Willett (2015) Personal communication, Jason Christopher Willett, U.S. Geological Survey and Gopi Manne, Eastern Research Group, Inc. September 9, 2015.

Ammonia Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

Bark (2004) *Coffeyville Nitrogen Plant*. December 15, 2004. Available online at:
[<http://www.gasification.org/uploads/downloads/Conferences/2003/07BARK.pdf>](http://www.gasification.org/uploads/downloads/Conferences/2003/07BARK.pdf).

Coffeyville Resources Nitrogen Fertilizers (2012) Nitrogen Fertilizer Operations. Available online at:
[<http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>](http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html).

Coffeyville Resources Nitrogen Fertilizers (2011) Nitrogen Fertilizer Operations. Available online at:
[<http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>](http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html).

Coffeyville Resources Nitrogen Fertilizers (2010) Nitrogen Fertilizer Operations. Available online at:
[<http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>](http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html).

Coffeyville Resources Nitrogen Fertilizers (2009) Nitrogen Fertilizer Operations. Available online at:
[<http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html>](http://coffeyvillegroup.com/NitrogenFertilizerOperations/index.html).

Coffeyville Resources Nitrogen Fertilizers, LLC (2005 through 2007a) Business Data. Available online at:
[<http://www.coxyvillegroup.com/businessSnapshot.asp>](http://www.coxyvillegroup.com/businessSnapshot.asp).

Coffeyville Resources Nitrogen Fertilizers (2007b) Nitrogen Fertilizer Operations. Available online at:
[<http://coffeyvillegroup.com/nitrogenMain.aspx>](http://coffeyvillegroup.com/nitrogenMain.aspx).

Coffeyville Resources Energy, Inc. (CVR) (2015) *CVR Energy, Inc. 2014 Annual Report*. Available online at:
[<http://cvrenergy.com>](http://cvrenergy.com).

CVR (2014) *CVR Energy, Inc. 2013 Annual Report*. Available online at: <<http://cvrenergy.com>>.

CVR (2012) *CVR Energy, Inc. 2012 Annual Report*. Available online at: <<http://cvrenergy.com>>.

EFMA (2000a) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 1 of 8: Production of Ammonium. Available online at:
[<http://fertilizerseurope.com/site/index.php?id=390>](http://fertilizerseurope.com/site/index.php?id=390).

EFMA (2000b) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate. Available online at:
[<http://fertilizerseurope.com/site/index.php?id=390>](http://fertilizerseurope.com/site/index.php?id=390).

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2011) *Current Industrial Reports Fertilizer Materials and Related Products: 2010 Summary*. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2010) *Current Industrial Reports Fertilizer Materials and Related Products: 2009 Summary*. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2009) *Current Industrial Reports Fertilizer Materials and Related Products: 2008 Summary*. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2008) *Current Industrial Reports Fertilizer Materials and Related Products: 2007 Summary*. Available online at: <<http://www.census.gov/cir/www/325/mq325b/mq325b075.xls>>.

U.S. Census Bureau (2007) *Current Industrial Reports Fertilizer Materials and Related Products: 2006 Summary*. Available online at: <<http://www.census.gov/industry/1/mq325b065.pdf>>.

U.S. Census Bureau (2006) *Current Industrial Reports Fertilizer Materials and Related Products: 2005 Summary*. Available online at: <<http://www.census.gov/cir/www/325/mq325b.html>>.

U.S. Census Bureau (2004, 2005) *Current Industrial Reports Fertilizer Materials and Related Products: Fourth Quarter Report Summary*. Available online at: <<http://www.census.gov/cir/www/325/mq325b.html>>.

U.S. Census Bureau (1998 through 2003) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Reports Summary*. Available online at: <<http://www.census.gov/cir/www/325/mq325b.html>>.

U.S. Census Bureau (1991 through 1994) *Current Industrial Reports Fertilizer Materials Annual Report*. Report No. MQ28B. U.S. Census Bureau, Washington, D.C.

United States Geological Survey (USGS) (2015) 2013 Minerals Yearbook: Nitrogen [Advance Release]. August 2015. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2013-nitro.pdf>>.

USGS (2014) 2012 Minerals Yearbook: Nitrogen [Advance Release]. September 2014. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2012-nitro.pdf>>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>>.

Urea Consumption for Non-Agricultural Purposes

EFMA (2000) *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet No. 5 of 8: Production of Urea and Urea Ammonium Nitrate.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

TFI (2002) *U.S. Nitrogen Imports/Exports Table*. The Fertilizer Institute. Available online at: <<http://www.tfi.org/statistics/usnexusim.asp>>. August 2002.

U.S. Census Bureau (2001 through 2011) *Current Industrial Reports Fertilizer Materials and Related Products: Annual Summary*. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/index.html>.

U.S. Department of Agriculture (2012) Economic Research Service Data Sets, Data Sets, U.S. Fertilizer Imports/Exports: Standard Tables. Available online at: <<http://www.ers.usda.gov/data-products/fertilizer-importsexports/standard-tables.aspx>>.

U.S. ITC (2002) *United States International Trade Commission Interactive Tariff and Trade DataWeb, Version 2.5.0*. Available online at: <http://dataweb.usitc.gov/scripts/user_set.asp>. August 2002.

United States Geological Survey (USGS) (2014 through 2015) Minerals Yearbook: Nitrogen [Advance Release]. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>>.

USGS (1994 through 2009) Minerals Yearbook: Nitrogen. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/>>.

Nitric Acid Production

Climate Action Reserve (CAR) (2013) Project Report. Available online at: <<https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111>>. Accessed on 18 January 2013.

Desai (2012) Personal communication. Mausami Desai, U.S. Environmental Protection Agency, January 25, 2012.

EPA (2015) Greenhouse Gas Reporting Program (GHGRP). Aggregation of Reported Facility Level Data under Subpart V -National Nitric Acid Production for Calendar Years 2010 through 2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2013) *Draft Nitric Acid Database*. U.S. Environmental Protection Agency, Office of Air and Radiation. September, 2010.

EPA (2012) Memorandum from Mausami Desai, U.S. EPA to Mr. Bill Herz, The Fertilizer Institute. November 26, 2012.

EPA (2010) *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. December 2010. Available online at: <<http://www.epa.gov/nsr/ghgdocs/nitricacid.pdf>>.

EPA (1998) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. February 1998.

IPCC (2007) Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2010a) *Current Industrial Reports. Fertilizers and Related Chemicals: 2009*. “Table 1: Summary of Production of Principle Fertilizers and Related Chemicals: 2009 and 2008.” June, 2010. MQ325B(08)-5. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2010b) Personal communication between Hilda Ward (of U.S. Census Bureau) and Caroline Cochran (of ICF International). October 26, 2010 and November 5, 2010.

U.S. Census Bureau (2009) *Current Industrial Reports. Fertilizers and Related Chemicals: 2008*. “Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2004 to 2008.” June, 2009. MQ325B(08)-5. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

U.S. Census Bureau (2008) *Current Industrial Reports. Fertilizers and Related Chemicals: 2007*. “Table 1: Shipments and Production of Principal Fertilizers and Related Chemicals: 2003 to 2007.” June, 2008. MQ325B(07)-5. Available online at: <http://www.census.gov/manufacturing/cir/historical_data/mq325b/index.html>.

Adipic Acid Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

C&EN (1995) “Production of Top 50 Chemicals Increased Substantially in 1994.” *Chemical & Engineering News*, 73(15):17. April 10, 1995.

C&EN (1994) “Top 50 Chemicals Production Rose Modestly Last Year.” *Chemical & Engineering News*, 72(15):13. April 11, 1994.

C&EN (1993) “Top 50 Chemicals Production Recovered Last Year.” *Chemical & Engineering News*, 71(15):11. April 12, 1993.

C&EN (1992) “Production of Top 50 Chemicals Stagnates in 1991.” *Chemical & Engineering News*, 70(15): 17. April 13, 1992.

CMR (2001) “Chemical Profile: Adipic Acid.” *Chemical Market Reporter*. July 16, 2001.

CMR (1998) “Chemical Profile: Adipic Acid.” *Chemical Market Reporter*. June 15, 1998.

CW (2005) “Product Focus: Adipic Acid.” *Chemical Week*. May 4, 2005.

CW (1999) “Product Focus: Adipic Acid/Adiponitrile.” *Chemical Week*, p. 31. March 10, 1999.

Desai (2011a) Personal communication. Mausami Desai, U.S. Environmental Protection Agency and Roy Nobel, Ascend Performance Materials, October 18, 2011.

Desai (2011b) Personal communication. Mausami Desai, U.S. Environmental Protection Agency with Steve Zuiss of Invista, November 18, 2011.

Desai (2010) Personal communication. Mausami Desai, U.S. Environmental Protection Agency with Steve Zuiss of Invista, October 15, 2010.

EPA (2014 through 2015) Greenhouse Gas Reporting Program. Annual Detailed Data for Additional Industry Types (Adipic Acid Tab). Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C. Accessed on October 7, 2015, Available online at: <<http://www2.epa.gov/ghg-reporting/ghg-reporting-program-data-sets>>.

EPA (2012) Analysis of Greenhouse Gas Reporting Program data – Subpart E (Adipic Acid), Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

ICIS (2007) “Adipic Acid.” *ICIS Chemical Business Americas*. July 9, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Reimer, R.A., Slaten, C.S., Seapan, M., Koch, T.A. and Triner, V.G. (1999) “Implementation of Technologies for Abatement of N₂O Emissions Associated with Adipic Acid Manufacture.” Proceedings of the 2nd Symposium on Non-CO₂ Greenhouse Gases (NCGG-2), Noordwijkerhout, The Netherlands, 8-10 Sept. 1999, Ed. J. van Ham *et al.*, Kluwer Academic Publishers, Dordrecht, pp. 347-358.

SEI (2010) *Industrial N₂O Projects Under the CDM: Adipic Acid – A Case for Carbon Leakage?* Stockholm Environment Institute Working Paper WP-US-1006. October 9, 2010.

Thiemens, M.H., and W.C. Troxler (1991) “Nylon production; an unknown source of atmospheric nitrous oxide.” *Science* 251:932-934.

VA DEQ (2010) Personal communication. Stanley Faggert, Virginia Department of Environmental Quality and Joseph Herr, ICF International. March 12, 2010.

VA DEQ (2009) Personal communication. Stanley Faggert, Virginia Department of Environmental Quality and Joseph Herr, ICF International. October 26, 2009.

VA DEQ (2006) Virginia Title V Operating Permit. Honeywell International Inc. Hopewell Plant. Virginia Department of Environmental Quality. Permit No. PRO50232. Effective January 1, 2007.

Silicon Carbide Production

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

U.S. Census Bureau (2005 through 2015) *U.S. International Trade Commission (USITC) Trade DataWeb*. Available online at: <<http://dataweb.usitc.gov/>>.

United States Geological Survey (USGS) (2015a) *Minerals Industry Surveys: Abrasives (Manufactured) in First Quarter of 2015*. U.S. Geological Survey, Reston, VA. September 2015. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/index.html>>.

USGS (1991a through 2015b) *Minerals Yearbook: Manufactured Abrasives Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/abrasives/>>.

USGS (1991b through 2013) *Minerals Yearbook: Silicon Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/silicon/>>.

Titanium Dioxide Production

Gambogi, J. (2002) Telephone communication. Joseph Gambogi, Commodity Specialist, U.S. Geological Survey and Philip Groth, ICF International. November 2002.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

United States Geological Survey (USGS) (1991 through 2015b) *Minerals Yearbook: Titanium*. U.S. Geological Survey, Reston, VA.

USGS (2015a) *2015 Mineral Commodity Summary: Titanium and Titanium Dioxide*. U.S. Geological Survey, Reston, VA. January, 2015.

Soda Ash Production and Consumption

Kostick, D. S. (2012) Personal communication. Dennis S. Kostick of U.S. Department of the Interior - U.S. Geological Survey, Soda Ash Commodity Specialist with Gopi Manne and Bryan Lange of Eastern Research Group, Inc. October 2012.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

United States Geological Survey (USGS) (2015a) Mineral Industry Surveys: Soda Ash in July 2015. U.S. Geological Survey, Reston, VA. September, 2015.

USGS (1994 through 2015b) *Minerals Yearbook: Soda Ash Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (1995a) Trona Resources in the Green River Basin, Southwest Wyoming. U.S. Department of the Interior, U.S. Geological Survey. Open-File Report 95-476. Wiig, Stephen, Grundy, W.D., Dyni, John R.

Petrochemical Production

ACC (2015) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

ACC (2014a) *U.S. Chemical Industry Statistical Handbook*. American Chemistry Council, Arlington, VA.

ACC (2014b) Business of Chemistry (Annual Data). American Chemistry Council, Arlington, VA.

ACC (2002, 2003, 2005 through 2011) *Guide to the Business of Chemistry*. American Chemistry Council, Arlington, VA.

AN (2014) *About Acrylonitrile: Production*. AN Group, Washington, D.C. Available online at: <<http://www.angroup.org/about/production.cfm>>

EPA Greenhouse Gas Reporting Program (2015) Aggregation of Reported Facility Level Data under Subpart X - National Petrochemical Production for Calendar Years 2010 through 2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA Greenhouse Gas Reporting Program (2014) Aggregation of Reported Facility Level Data under Subpart X - National Petrochemical Production for Calendar Years 2010 through 2013. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

EPA (2008) *Technical Support Document for the Petrochemical Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases*. U.S. Environmental Protection Agency. September 2008.

EPA (2000) *Economic Impact Analysis for the Proposed Carbon Black Manufacturing NESHAP*, U.S. Environmental Protection Agency. Research Triangle Park, NC. EPA-452/D-00-003. May 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jordan, J. (2011) Personal communication, Jim Jordan of Jordan Associates on behalf of the Methanol Institute and Pier LaFarge, ICF International. October 18, 2011

Johnson, G. L. (2005 through 2010) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caroline Cochran, ICF International. September 2010.

Johnson, G. L. (2003) Personal communication. Greg Johnson of Liskow & Lewis, on behalf of the International Carbon Black Association (ICBA) and Caren Mintz, ICF International November 2003.

HCFC-22 Production

ARAP (2010) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 10, 2010.

ARAP (2009) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. September 21, 2009.

ARAP (2008) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 17, 2008.

ARAP (2007) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. October 2, 2007.

ARAP (2006) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. July 11, 2006.

ARAP (2005) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 9, 2005.

ARAP (2004) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. June 3, 2004.

ARAP (2003) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 18, 2003.

ARAP (2002) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 7, 2002.

ARAP (2001) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger of the U.S. Environmental Protection Agency. August 6, 2001.

ARAP (2000) Electronic mail communication from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Sally Rand of the U.S. Environmental Protection Agency. August 13, 2000.

ARAP (1999) Facsimile from Dave Stirpe, Executive Director, Alliance for Responsible Atmospheric Policy to Deborah Ottinger Schaefer of the U.S. Environmental Protection Agency. September 23, 1999.

ARAP (1997) Letter from Dave Stirpe, Director, Alliance for Responsible Atmospheric Policy to Elizabeth Dutrow of the U.S. Environmental Protection Agency. December 23, 1997.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

RTI (2008) “Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 2006.” Report prepared by RTI International for the Climate Change Division. March, 2008.

RTI (1997) “Verification of Emission Estimates of HFC-23 from the Production of HCFC-22: Emissions from 1990 through 1996.” Report prepared by Research Triangle Institute for the Cadmus Group. November 25, 1997; revised February 16, 1998.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

Carbon Dioxide Consumption

Allis, R. et al. (2000) *Natural CO₂ Reservoirs on the Colorado Plateau and Southern Rocky Mountains: Candidates for CO₂ Sequestration*. Utah Geological Survey and Utah Energy and Geoscience Institute. Salt Lake City, Utah.

ARI (1990 through 2010) *CO₂ Use in Enhanced Oil Recovery*. Deliverable to ICF International under Task Order 102, July 15, 2011.

ARI (2007) *CO₂-EOR: An Enabling Bridge for the Oil Transition*. Presented at “Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions.” Washington, D.C. April 20-21, 2007.

ARI (2006) *CO₂-EOR: An Enabling Bridge for the Oil Transition*. Presented at “Modeling the Oil Transition—a DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions.” Washington, D.C. April 20-21, 2006.

Broadhead (2003) Personal communication. Ron Broadhead, Principal Senior Petroleum Geologist and Adjunct faculty, Earth and Environmental Sciences Department, New Mexico Bureau of Geology and Mineral Resources, and Robin Pestrusak, ICF International. September 5, 2003.

COGCC (1999 through 2009) Monthly CO₂ Produced by County. Available online at: <<http://cogcc.state.co.us/COGCCReports/production.aspx?id=MonthlyCO2ProdByCounty>>. Accessed October 2014.

Denbury Resources Inc. (2002 through 2010) Annual Report: 2001 through 2009, Form 10-K. Available online at: <<http://www.denbury.com/investor-relations/SEC-Filings/SEC-Filings-Details/default.aspx?FilingId=9823015>>. Accessed September 2014.

EPA Greenhouse Gas Reporting Program (2015). Aggregation of Reported Facility Level Data under Subpart PP - National Level CO₂ Transferred for Food & Beverage Applications for Calendar Years 2010 through 2014. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

New Mexico Bureau of Geology and Mineral Resources (2006) Natural Accumulations of Carbon Dioxide in New Mexico and Adjacent Parts of Colorado and Arizona: Commercial Accumulation of CO₂. Available online at: <<http://geoinfo.nmt.edu/staff/broadhead/CO2.html#commercial>>.

Phosphoric Acid Production

EFMA (2000) “Production of Phosphoric Acid.” *Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry*. Booklet 4 of 8. European Fertilizer Manufacturers Association. Available online at: <<http://www.efma.org/Publications/BAT%202000/Bat04/section04.asp>>.

FIPR (2003a) “Analyses of Some Phosphate Rocks.” Facsimile Gary Albarelli, the Florida Institute of Phosphate Research, Bartow, Florida, to Robert Lanza, ICF International. July 29, 2003.

FIPR (2003b) Florida Institute of Phosphate Research. Personal communication. Mr. Michael Lloyd, Laboratory Manager, FIPR, Bartow, Florida, to Mr. Robert Lanza, ICF International. August 2003.

NCDENR (2013) North Carolina Department of Environment and Natural Resources, Title V Air Permit Review for PCS Phosphate Company, Inc. – Aurora. Available online at: <http://www.ncair.org/permits/permit_reviews/PCS_rev_08282012.pdf>. Accessed on January 25, 2013.

United States Geological Survey (USGS) (1994 through 2015b) *Minerals Yearbook. Phosphate Rock Annual Report*. U.S. Geological Survey, Reston, VA.

USGS (2015a) Mineral Commodity Summaries: Phosphate Rock 2015. January 2015. U.S. Geological Survey, Reston, VA. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2015-phosp.pdf>.

USGS (2012b) Personal communication between Stephen Jasinski (USGS) and Mausami Desai (EPA) on October 12, 2012.

Iron and Steel Production and Metallurgical Coke Production

AISI (2004 through 2015a) *Annual Statistical Report*, American Iron and Steel Institute, Washington, D.C.

AISI (2006 through 2014b) Personal communication, Mausami Desai, U.S. EPA, and American Iron and Steel Institute, December 8, 2014.

AISI (2008c) Personal communication, Mausami Desai, U.S. EPA, and Bruce Steiner, Technical Consultant with the American Iron and Steel Institute, October 2008.

Carroll (2015) Personal communication, Mausami Desai, U.S. EPA, and Colin P. Carroll, Director of Environment, Health and Safety, American Iron and Steel Institute, September 2015.

DOE (2000) *Energy and Environmental Profile of the U.S. Iron and Steel Industry*. Office of Industrial Technologies, U.S. Department of Energy. August 2000. DOE/EE-0229.EIA

EIA (1998 through 2014) *Quarterly Coal Report: October-December*, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0121.

EIA (2015a) *Natural Gas Annual 2014*, Energy Information Administration, U.S. Department of Energy. Washington, D.C. DOE/EIA-0131(06).

EIA (2015b) *Monthly Energy Review, December 2015*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. DOE/EIA-0035(2015/12).

EIA (1992) Coal and lignite production. *EIA State Energy Data Report 1992*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

EPA (2010) Carbon Content Coefficients Developed for EPA's Mandatory Reporting Rule. Office of Air and Radiation, Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

Fenton (2015) Personal communication. Michael Fenton, Commodity Specialist, U.S. Geological Survey and Marty Wolf, Eastern Research Group. September 16, 2015.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1995) "Volume 3: Greenhouse Gas Inventory Reference Manual. Table 2-2". *IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency. IPCC WG1 Technical Support Unit, United Kingdom.

United States Geological Survey (USGS) (1991 through 2014) *USGS Minerals Yearbook – Iron and Steel Scrap*. U.S. Geological Survey, Reston, VA.

Ferroalloy Production

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Onder, H., and E.A. Bagdoyan (1993) Everything You've Always Wanted to Know about Petroleum Coke. Allis Mineral Systems.

United States Geological Survey (USGS) (2015a) *2012 Minerals Yearbook: Ferroalloys*. U.S. Geological Survey, Reston, VA. April 2015.

USGS (2015b) *Mineral Industry Surveys: Silicon in June 2015*. U.S. Geological Survey, Reston, VA. September 2015.

USGS (2014) *Mineral Industry Surveys: Silicon in September 2014*. U.S. Geological Survey, Reston, VA. December 2014.

USGS (1996 through 2013) *Minerals Yearbook: Silicon*. U.S. Geological Survey, Reston, VA.

Aluminum Production

EPA (2016) Greenhouse Gas Reporting Program (GHGRP). Envirofacts, Subpart: F Aluminum Production. Available online at: <<http://www.epa.gov/enviro/facts/ghg/search.html>>. Accessed on March 17, 2016.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

USAA (2016) *U.S. Primary Aluminum Production: Report for February 2016*. U.S. Aluminum Association, Washington, D.C. March, 2016.

USAA (2015) *U.S. Primary Aluminum Production: Report for June 2015*. U.S. Aluminum Association, Washington, D.C. July, 2015.

USAA (2014) *U.S. Primary Aluminum Production 2013*. U.S. Aluminum Association, Washington, D.C. October, 2014.

USAA (2013) *U.S. Primary Aluminum Production 2012*. U.S. Aluminum Association, Washington, D.C. January, 2013.

USAA (2012) *U.S. Primary Aluminum Production 2011*. U.S. Aluminum Association, Washington, D.C. January, 2012.

USAA (2011) *U.S. Primary Aluminum Production 2010*. U.S. Aluminum Association, Washington, D.C.

USAA (2010) *U.S. Primary Aluminum Production 2009*. U.S. Aluminum Association, Washington, D.C.

USAA (2008, 2009) *U.S. Primary Aluminum Production*. U.S. Aluminum Association, Washington, D.C.

USAA (2004, 2005, 2006) *Primary Aluminum Statistics*. U.S. Aluminum Association, Washington, D.C.

USGS (2015a) *2014 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.

USGS (2015b) *2015 Mineral Commodity Summaries: Aluminum*. U.S. Geological Survey, Reston, VA.

- USGS (2015c) *Mineral Industry Surveys: Aluminum in December 2014*. U.S. Geological Survey, Reston, VA.
- USGS (2014) *Mineral Industry Surveys: Aluminum in December 2013*. U.S. Geological Survey, Reston, VA.
- USGS (2007) *2006 Mineral Yearbook: Aluminum*. U.S. Geological Survey, Reston, VA.
- USGS (1995, 1998, 2000, 2001, 2002) *Minerals Yearbook: Aluminum Annual Report*. U.S. Geological Survey, Reston, VA.

Magnesium Production and Processing

- Bartos S., C. Laush, J. Scharfenberg, and R. Kantamaneni (2007) “Reducing greenhouse gas emissions from magnesium die casting.” *Journal of Cleaner Production*, 15: 979-987, March.
- EPA (2015) Envirofacts. Greenhouse Gas Reporting Program (GHGRP), Subpart T: Magnesium Production and Processing. Available online at: <<http://www.epa.gov/enviro/facts/ghg/search.html>>. Accessed on March, 2016.
- Gjestland, H. and D. Magers (1996) “Practical Usage of Sulphur [Sulfur] Hexafluoride for Melt Protection in the Magnesium Die Casting Industry.” #13, *1996 Annual Conference Proceedings*, International Magnesium Association. Ube City, Japan.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- RAND (2002) RAND Environmental Science and Policy Center, “Production and Distribution of SF₆ by End-Use Applications” Katie D. Smythe. *International Conference on SF₆ and the Environment: Emission Reduction Strategies*. San Diego, CA. November 21-22, 2002.
- USGS (2014, 2013, 2012, 2011, 2010, 2009, 2008, 2007, 2006, 2005a, 2003, 2002) *Minerals Yearbook: Magnesium Annual Report*. U.S. Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/index.html#mis>>.
- USGS (2010b) *Mineral Commodity Summaries: Magnesium Metal*. U.S. Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2010-mgmet.pdf>>.
- USGS (2005b) Personal Communication between Deborah Kramer of the USGS and Jeremy Schafenberg of ICF Consulting.

Lead Production

- Dutrzac, J.E., V. Ramachandran, and J.A. Gonzalez (2000) *Lead-Zinc 2000*. The Minerals, Metals, and Materials Society.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- Morris, D., F.R. Steward, and P. Evans (1983) *Energy Efficiency of a Lead Smelter*. Energy 8(5):337-349.
- Sjardin, M. (2003) *CO₂ Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.
- Ullman (1997) *Ullman's Encyclopedia of Industrial Chemistry: Fifth Edition*. Volume A5. John Wiley and Sons.
- United States Geological Survey (USGS) (2015) *2015 Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. January 2015.
- USGS (2014) *Mineral Commodity Summary, Lead*. U.S. Geological Survey, Reston, VA. February 2014.
- USGS (1995 through 2013) *Minerals Yearbook: Lead Annual Report*. U.S. Geological Survey, Reston, VA.

Zinc Production

Horsehead Corp. (2015) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2014. Available online at: <<http://www.sec.gov/Archives/edgar/data/1385544/000138554415000005/zinc-2014123110k.htm>>. Submitted on March 2, 2015.

Horsehead Corp. (2014) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2013. Available online at: <<http://www.sec.gov/Archives/edgar/data/1385544/000138554414000003/zinc-2013123110k.htm>>. Submitted on March 13, 2014.

Horsehead Corp. (2013) Form 10-k, Annual Report for the Fiscal Year Ended December 31, 2012. Available online at: <<http://www.sec.gov/Archives/edgar/data/1385544/000119312513110431/0001193125-13-110431-index.htm>>. Submitted March 18, 2013.

Horsehead Corp. (2012a) Form 10-k, Annual Report for the Fiscal Year Ended December, 31, 2011. Available online at: <<http://www.sec.gov/Archives/edgar/data/1385544/000119312512107345/d293011d10k.htm>>. Submitted on March 9, 2012.

Horsehead Corp. (2012b) *Horsehead's New Zinc Plant and its Impact on the Zinc Oxide Business*. February 22, 2012. Available online at: <<http://www.horsehead.net/downloadAttachmentNDO.php?ID=118>>. Accessed on September 10, 2015.

Horsehead Corp. (2011) 10-k Annual Report for the Fiscal Year Ended December, 31 2010. Available online at: <<http://google.brand.edgar-online.com/default.aspx?sym=zinc>>. Submitted on March 16, 2011.

Horsehead Corp. (2010a) 10-k Annual Report for the Fiscal Year Ended December, 31 2009. Available online at: <<http://google.brand.edgar-online.com/default.aspx?sym=zinc>>. Submitted on March 16, 2010.

Horsehead Corp. (2010b) *Horsehead Holding Corp. Provides Update on Operations at its Monaca, PA Plant*. July 28, 2010. Available online at: <<http://www.horsehead.net/pressreleases.php?showall=no&news=&ID=65>>.

Horsehead Corp (2008) 10-k Annual Report for the Fiscal Year Ended December 31, 2007. Available online at: <<http://google.brand.edgar-online.com/default.aspx?sym=zinc>>. Submitted on March 31, 2008.

Horsehead Corp (2007) Registration Statement (General Form) S-1. Available online at <<http://google.brand.edgar-online.com/default.aspx?sym=zinc>>. Submitted on April 13, 2007.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

PIZO (2014) Available online at <<http://pizotech.com/index.html>>. Accessed on December 9, 2014.

PIZO (2012) Available online at <<http://pizotech.com/index.html>>. Accessed on October 10, 2012.

Sjardin (2003) *CO₂ Emission Factors for Non-Energy Use in the Non-Ferrous Metal, Ferroalloys and Inorganics Industry*. Copernicus Institute. Utrecht, the Netherlands.

Steel Dust Recycling (SDR) (2015) Personal communication. Jeremy Whitten, EHS Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. September 22, 2015.

SDR (2014) Personal communication. Art Rowland, Plant Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. December 9, 2014.

SDR (2013) Available online at <<http://steeldust.com/home.htm>>. Accessed on October 29, 2013.

SDR (2012) Personal communication. Art Rowland, Plant Manager, Steel Dust Recycling LLC and Gopi Manne, Eastern Research Group, Inc. October 5, 2012.

United States Geological Survey (USGS) (2015) *2015 Mineral Commodity Summary: Zinc*. U.S. Geological Survey, Reston, VA. January 2015.

USGS (1995 through 2014) *Minerals Yearbook: Zinc Annual Report*. U.S. Geological Survey, Reston, VA.

Semiconductor Manufacture

Burton, C.S., and R. Beizaie (2001) "EPA's PFC Emissions Model (PEVM) v. 2.14: Description and Documentation" prepared for Office of Global Programs, U. S. Environmental Protection Agency, Washington, DC. November 2001.

Citigroup Smith Barney (2005) *Global Supply/Demand Model for Semiconductors*. March 2005.

Doering, R. and Nishi, Y (2000) "Handbook of Semiconductor Manufacturing Technology", Marcel Dekker, New York, USA, 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

ISMI (2009) *Analysis of Nitrous Oxide Survey Data*. Walter Worth. June 8, 2009. Available online at: <<http://sematech.org/docubase/document/5015atr.pdf>>

ITRS (2007, 2008, 2011, 2013) *International Technology Roadmap for Semiconductors: 2006 Update*, January 2007; *International Technology Roadmap for Semiconductors: 2007 Edition*, January 2008; *International Technology Roadmap for Semiconductors: 2011, January 2012; Update, International Technology Roadmap for Semiconductors: 2013 Edition*, Available online at: <<http://www.itrs.net/Links/2013ITRS/Home2013.htm>>. These and earlier editions and updates are available online at: <<http://public.itrs.net>>. Information about the number of interconnect layers for years 1990–2010 is contained in Burton and Beizaie, 2001. PEVM is updated using new editions and updates of the ITRS, which are published annually.

SEMI - Semiconductor Equipment and Materials Industry (2013) *World Fab Forecast, May 2013 Edition*.

SEMI - Semiconductor Equipment and Materials Industry (2012) *World Fab Forecast, August 2012 Edition*.

Semiconductor Industry Association (SIA) (2009-2011) STATS: SICAS Capacity and Utilization Rates Q1-Q4 2008, Q1-Q4 2009, Q1-Q4 2010. Available online at: <http://www.semiconductors.org/industry_statistics/semiconductor_capacity_utilization_sicas_reports/>.

United States Census Bureau (USCB) (2011, 2012, 2013, 2014) *Historical Data: Quarterly Survey of Plant Capacity Utilization*. Available online at: <https://www.census.gov/manufacturing/capacity/historical_data/index.html>

U.S. EPA (2006) *Uses and Emissions of Liquid PFC Heat Transfer Fluids from the Electronics Sector*. U.S. Environmental Protection Agency, Washington, DC. EPA-430-R-06-901.

U.S. EPA Greenhouse Gas Reporting Program (GHGRP) Envirofacts. Subpart I: Electronics Manufacture. Available online at: <<http://www.epa.gov/enviro/facts/ghg/search.html>>

VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

Substitution of Ozone Depleting Substances

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Electrical Transmission and Distribution

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press. Cambridge, United Kingdom.

Levin et al. (2010) “The Global SF₆ Source Inferred from Long-term High Precision Atmospheric Measurements and its Comparison with Emission Inventories.” *Atmospheric Chemistry and Physics*, 10: 2655–2662.

O’Connell, P., F. Heil, J. Henriot, G. Mauthe, H. Morrison, L. Neimeyer, M. Pittroff, R. Probst, J.P. Tailebois (2002) *SF₆ in the Electric Industry, Status 2000*, CIGRE. February 2002.

RAND (2004) “Trends in SF₆ Sales and End-Use Applications: 1961-2003,” Katie D. Smythe. *International Conference on SF₆ and the Environment: Emission Reduction Strategies*. RAND Environmental Science and Policy Center, Scottsdale, AZ. December 1-3, 2004.

UDI (2013). *2013 UDI Directory of Electric Power Producers and Distributors, 121st Edition*, Platts.

UDI (2010) *2010 UDI Directory of Electric Power Producers and Distributors, 118th Edition*, Platts.

UDI (2007) *2007 UDI Directory of Electric Power Producers and Distributors, 115th Edition*, Platts.

UDI (2004) *2004 UDI Directory of Electric Power Producers and Distributors, 112th Edition*, Platts.

UDI (2001) *2001 UDI Directory of Electric Power Producers and Distributors, 109th Edition*, Platts.

UNFCCC (2014) Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. United Nations Framework Convention on Climate Change, Warsaw. (FCCC/CP/2013/10/Add.3). January 31, 2014. Available online at: <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

Nitrous Oxide from Product Use

CGA (2003) “CGA Nitrous Oxide Abuse Hotline: CGA/NWSA Nitrous Oxide Fact Sheet.” Compressed Gas Association. November 3, 2003.

CGA (2002) “CGA/NWSA Nitrous Oxide Fact Sheet.” Compressed Gas Association. March 25, 2002.

Heydorn, B. (1997) “Nitrous Oxide—North America.” *Chemical Economics Handbook*, SRI Consulting. May 1997.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ottinger (2014) Personal communication. Deborah Ottinger (CCD, U.S. EPA) and Mausami Desai (U.S. EPA). Email received on January 29, 2014.

Tupman, M. (2003) Personal communication .Martin Tupman, Airgas Nitrous Oxide and Daniel Lieberman, ICF International. August 8, 2003.

Industrial Processes and Product Use Sources of Indirect Greenhouse Gases

EPA (2015) "1970-2014 Average annual emissions, all criteria pollutants in MS Excel." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.

EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.

EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

Agriculture

Enteric Fermentation

Archibeque, S. (2011) Personal Communication. Shawn Archibeque, Colorado State University, Fort Collins, Colorado and staff at ICF International.

Crutzen, P.J., I. Aselmann, and W. Seiler (1986) Methane Production by Domestic Animals, Wild Ruminants, Other Herbivores, Fauna, and Humans. *Tellus*, 38B:271-284.

Donovan, K. (1999) Personal Communication. Kacey Donovan, University of California at Davis and staff at ICF International.

Doren, P.E., J. F. Baker, C. R. Long and T. C. Cartwright (1989) Estimating Parameters of Growth Curves of Bulls, *J Animal Science* 67:1432-1445.

Enns, M. (2008) Personal Communication. Dr. Mark Enns, Colorado State University and staff at ICF International.

Galyean and Gleghorn (2001) Summary of the 2000 Texas Tech University Consulting Nutritionist Survey. Texas Tech University. Available online at: <http://www.depts.ttu.edu/afs/burnett_center/progress_reports/bc12.pdf>. June 2009.

Holstein Association (2010) *History of the Holstein Breed* (website). Available online at: <http://www.holsteinusa.com/holstein_breed/breedhistory.html>. Accessed September 2010.

ICF (2006) *Cattle Enteric Fermentation Model: Model Documentation*. Prepared by ICF International for the Environmental Protection Agency. June 2006.

ICF (2003) *Uncertainty Analysis of 2001 Inventory Estimates of Methane Emissions from Livestock Enteric Fermentation in the U.S.* Memorandum from ICF International to the Environmental Protection Agency. May 2003.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D. (2002) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and ICF International.

Johnson, D. (1999) Personal Communication. Don Johnson, Colorado State University, Fort Collins, and David Conneely, ICF International.

- Johnson, K. (2010) Personal Communication. Kris Johnson, Washington State University, Pullman, and ICF International.
- Kebreab E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *J. Anim. Sci.* 86: 2738-2748.
- Lippke, H., T. D. Forbes, and W. C. Ellis. (2000) Effect of supplements on growth and forage intake by stocker steers grazing wheat pasture. *J. Anim. Sci.* 78:1625-1635
- National Bison Association (2011) Handling & Carcass Info (on website). Available online at: <<http://www.bisoncentral.com/about-bison/handling-and-carcass-info>>. Accessed August 16, 2011.
- National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.
- NRC (1999) *1996 Beef NRC: Appendix Table 22*. National Research Council.
- NRC (1984) *Nutrient requirements for beef cattle (6th Ed.)*. National Academy Press, Washington, DC.
- Pinchak, W.E., D. R. Tolleson, M. McCloy, L. J. Hunt, R. J. Gill, R. J. Ansley, and S. J. Bevers (2004) Morbidity effects on productivity and profitability of stocker cattle grazing in the southern plains. *J. Anim. Sci.* 82:2773-2779.
- Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith (2003) Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. *J. Anim. Sci.* 81:984-996.
- Preston, R.L. (2010) “What's The Feed Composition Value of That Cattle Feed?” Beef Magazine, March 1, 2010. Available online at: <<http://beefmagazine.com/nutrition/feed-composition-tables/feed-composition-value-cattle--0301>>.
- Skogerboe, T. L., L. Thompson, J. M. Cunningham, A. C. Brake, V. K. Karle (2000) *The effectiveness of a single dose of doramectin pour-on in the control of gastrointestinal nematodes in yearling stocker cattle*. *Vet. Parasitology* 87:173-181.
- Soliva, C.R. (2006) Report to the attention of IPCC about the data set and calculation method used to estimate methane formation from enteric fermentation of agricultural livestock population and manure management in Swiss agriculture. On behalf of the Federal Office for the Environment (FOEN), Berne, Switzerland.
- USDA (2015) *Quick Stats: Agricultural Statistics Database*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: <<http://quickstats.nass.usda.gov/>>. Accessed August 3, 2015.
- USDA (2007) *Census of Agriculture: 2007 Census Report*. United States Department of Agriculture. Available online at: <<http://www.agcensus.usda.gov/Publications/2007/index.asp>>.
- USDA (2002) *Census of Agriculture: 2002 Census Report*. United States Department of Agriculture. Available online at: <<http://www.agcensus.usda.gov/Publications/2002/index.asp>>.
- USDA (1997) *Census of Agriculture: 1997 Census Report*. United States Department of Agriculture. Available online at: <<http://www.agcensus.usda.gov/Publications/1997/index.asp>>. Accessed July 18, 2011.
- USDA (1996) *Beef Cow/Calf Health and Productivity Audit (CHAPA): Forage Analyses from Cow/Calf Herds in 18 States*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: <<http://www.aphis.usda.gov/vs/ceah/cahm>>. March 1996.
- USDA (1992) *Census of Agriculture: 1992 Census Report*. United States Department of Agriculture. Available online at: <<http://www.agcensus.usda.gov/Publications/1992/index.asp>>. Accessed July 18, 2011.
- USDA:APHIS:VS (2010) *Beef 2007–08, Part V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08*. USDA–APHIS–VS, CEAH. Fort Collins, CO.
- USDA:APHIS:VS (2002) *Reference of 2002 Dairy Management Practices*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at: <<http://www.aphis.usda.gov/vs/ceah/cahm>>.
- USDA:APHIS:VS (1998) *Beef '97, Parts I-IV*. USDA–APHIS–VS, CEAH. Fort Collins, CO. Available online at: <http://www.aphis.usda.gov/animal_health/nahms/beefcowcalf/index.shtml#beef97>

USDA:APHIS:VS (1996) *Reference of 1996 Dairy Management Practices*. USDA—APHIS—VS, CEAH. Fort Collins, CO. Available online at: <<http://www.aphis.usda.gov/vs/ceah/cahm>>.

USDA:APHIS:VS (1994) *Beef Cow/Calf Health and Productivity Audit*. USDA—APHIS—VS, CEAH. Fort Collins, CO. Available online at: <<http://www.aphis.usda.gov/vs/ceah/cahm>>.

USDA:APHIS:VS (1993) *Beef Cow/Calf Health and Productivity Audit*. USDA—APHIS—VS, CEAH. Fort Collins, CO. August 1993. Available online at: <<http://www.aphis.usda.gov/vs/ceah/cahm>>.

Vasconcelos and Galyean (2007) *Nutritional recommendations of feedlot consulting nutritionists: The 2007 Texas Tech University Study*. *J. Anim. Sci.* 85:2772-2781.

Manure Management

Anderson, S. (2000) Personal Communication. Steve Anderson, Agricultural Statistician, National Agriculture Statistics Service, U.S. Department of Agriculture and Lee-Ann Tracy, ERG. Washington, D.C. May 31, 2000.

ASAE (1998) *ASAE Standards 1998, 45th Edition*. American Society of Agricultural Engineers. [St. Joseph, MI. Bryant, M.P., V.H. Varel, R.A. Frobish, and H.R. Isaacson (1976) In H.G. Schlegel (ed.)]; *Seminar on Microbial Energy Conversion*. E. Goltz KG. Göttingen, Germany.

Bush, E. (1998) Personal communication with Eric Bush, Centers for Epidemiology and Animal Health , U.S. Department of Agriculture regarding *National Animal Health Monitoring System's (NAHMS) Swine '95 Study*.

Deal, P. (2000) Personal Communication. Peter B. Deal, Rangeland Management Specialist, Florida Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 21, 2000.

EPA (2012) AgSTAR Anaerobic Digester Database. Available online at: <<http://www.epa.gov/agstar/projects/index.html#database>>.

EPA (2008) *Climate Leaders Greenhouse Gas Inventory Offset Project Methodology for Project Type Managing Manure with Biogas Recovery Systems*. Available online at: <http://www.epa.gov/climateleaders/documents/resources/ClimateLeaders_DraftManureOffsetProtocol.pdf>.

EPA (2006) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Winter 2006. Available online at: <<http://www.epa.gov/agstar/pdf/2006digest.pdf>>. Retrieved July 2006.

EPA (2005) *National Emission Inventory—Ammonia Emissions from Animal Agricultural Operations, Revised Draft Report*. U.S. Environmental Protection Agency. Washington, D.C. April 22, 2005. Available online at: <ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/nh3inventory_draft_042205.pdf>. Accessed August 2007.

EPA (2003) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Winter 2003. Available online at: <<http://www.epa.gov/agstar/pdf/2003digest.pdf>>. Retrieved July 2006.

EPA (2002a) *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System (NPDES) Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (CAFOs)*. U.S. Environmental Protection Agency. EPA-821-R-03-001. December 2002.

EPA (2002b) *Cost Methodology for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations*. U.S. Environmental Protection Agency. EPA-821-R-03-004. December 2002.

EPA (2000) *AgSTAR Digest*. Office of Air and Radiation, U.S. Environmental Protection Agency. Washington, D.C. Spring 2000. Available online at: <<http://www.epa.gov/agstar/news-events/digest/2000digest.pdf>>.

EPA (1992) *Global Methane Emissions from Livestock and Poultry Manure*, Office of Air and Radiation, U.S. Environmental Protection Agency. February 1992.

ERG (2010a) “Typical Animal Mass Values for Inventory Swine Categories.” Memorandum to EPA from ERG. July 19, 2010.

ERG (2010b) Telecon with William Boyd of USDA NRCS and Cortney Itle of ERG Concerning Updated VS and Nex Rates. August 8, 2010.

ERG (2010c) "Updating Current Inventory Manure Characteristics new USDA Agricultural Waste Management Field Handbook Values." Memorandum to EPA from ERG. August 13, 2010.

ERG (2008) "Methodology for Improving Methane Emissions Estimates and Emission Reductions from Anaerobic Digestion System for the 1990-2007 Greenhouse Gas Inventory for Manure Management." Memorandum to EPA from ERG. August 18, 2008.

ERG (2003a) "Methodology for Estimating Uncertainty for Manure Management Greenhouse Gas Inventory." Contract No. GS-10F-0036, Task Order 005. Memorandum to EPA from ERG, Lexington, MA. September 26, 2003.

ERG (2003b) "Changes to Beef Calves and Beef Cows Typical Animal Mass in the Manure Management Greenhouse Gas Inventory." Memorandum to EPA from ERG, October 7, 2003.

ERG (2001) *Summary of development of MDP Factor for methane conversion factor calculations*. ERG, Lexington, MA. September 2001.

ERG (2000a) *Calculations: Percent Distribution of Manure for Waste Management Systems*. ERG, Lexington, MA. August 2000.

ERG (2000b) *Discussion of Methodology for Estimating Animal Waste Characteristics* (Summary of B₀ Literature Review). ERG, Lexington, MA. June 2000.

Garrett, W.N. and D.E. Johnson (1983) "Nutritional energetics of ruminants." *Journal of Animal Science*, 57(suppl.2):478-497.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle (2000) "Evaluating annual nitrous oxide fluxes at the ecosystem scale." *Global Biogeochemical Cycles*, 14(4):1061-1070.

Hashimoto, A.G. (1984) "Methane from Swine Manure: Effect of Temperature and Influent Substrate Composition on Kinetic Parameter (k)." *Agricultural Wastes*, 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen (1981) "Ultimate Methane Yield from Beef Cattle Manure; Effect of Temperature, Ration Constituents, Antibiotics and Manure Age." *Agricultural Wastes*, 3:241-256.

Hill, D.T. (1984) "Methane Productivity of the Major Animal Types." *Transactions of the ASAE*, 27(2):530-540.

Hill, D.T. (1982) "Design of Digestion Systems for Maximum Methane Production." *Transactions of the ASAE*, 25(1):226-230.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Johnson, D. (2000) Personal Communication. Dan Johnson, State Water Management Engineer, California Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 23, 2000.

Lange, J. (2000) Personal Communication. John Lange, Agricultural Statistician, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. Washington, D.C. May 8, 2000.

Meagher, M. (1986) *Bison. Mammalian Species*. 266: 1-8.

Miller, P. (2000) Personal Communication. Paul Miller, Iowa Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 12, 2000.

Milton, B. (2000) Personal Communication. Bob Milton, Chief of Livestock Branch, U.S. Department of Agriculture, National Agriculture Statistics Service and Lee-Ann Tracy, ERG. May 1, 2000.

Moffroid, K. and D. Pape. (2014) *1990-2013 Volatile Solids and Nitrogen Excretion Rates*. Dataset to EPA from ICF International. August 2014.

Morris, G.R. (1976) *Anaerobic Fermentation of Animal Wastes: A Kinetic and Empirical Design Fermentation*. M.S. Thesis. Cornell University.

National Bison Association (1999) Total Bison Population—1999. Report provided during personal email communication with Dave Carter, Executive Director, National Bison Association July 19, 2011.

NOAA (2014) *National Climate Data Center (NCDC)*. Available online at:
<<ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/>> (for all states except Alaska and Hawaii) and
<<ftp://ftp.ncdc.noaa.gov/pub/data/gsod/2008/>>. (for Alaska and Hawaii). September 2014.

Ott, S.L. (2000) *Dairy '96 Study*. Stephen L. Ott, Animal and Plant Health Inspection Service, U.S. Department of Agriculture. June 19, 2000.

Poe, G., N. Bills, B. Bellows, P. Crosscombe, R. Koelsch, M. Kreher, and P. Wright (1999) *Staff Paper Documenting the Status of Dairy Manure Management in New York: Current Practices and Willingness to Participate in Voluntary Programs*. Department of Agricultural, Resource, and Managerial Economics; Cornell University, Ithaca, New York, September.

Safley, L.M., Jr. (2000) Personal Communication. Deb Bartram, ERG and L.M. Safley, President, Agri-Waste Technology. June and October 2000.

Safley, L.M., Jr. and P.W. Westerman (1990) "Psychrophilic anaerobic digestion of animal manure: proposed design methodology." *Biological Wastes*, 34:133-148.

Stettler, D. (2000) Personal Communication. Don Stettler, Environmental Engineer, National Climate Center, Oregon Natural Resource Conservation Service and Lee-Ann Tracy, ERG. June 27, 2000.

Sweeten, J. (2000) Personal Communication. John Sweeten, Texas A&M University and Indra Mitra, ERG. June 2000.

UEP (1999) *Voluntary Survey Results—Estimated Percentage Participation/Activity*. Caged Layer Environmental Management Practices, Industry data submissions for EPA profile development, United Egg Producers and National Chicken Council. Received from John Thorne, Capitolink. June 2000.

USDA (2015a) *Quick Stats: Agricultural Statistics Database*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. Available online at: <<http://quickstats.nass.usda.gov/>>.

USDA (2015b) *Chicken and Eggs 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2015. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2015c) *Poultry - Production and Value 2014 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2015. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2014a) *1987, 1992, 1997, 2002, 2007, and 2012 Census of Agriculture*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2014. Available online at:
<<http://www.nass.usda.gov/census/>>.

USDA (2014b) *Chicken and Eggs 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2014. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2014c) *Poultry - Production and Value 2013 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2014. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2013a) *Chicken and Eggs 2012 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2013. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2013b) *Poultry - Production and Value 2012 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2013. Available online at:
<<http://www.nass.usda.gov/Publications/index.asp>>.

USDA (2012a) *Chicken and Eggs 2011 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2012. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2012b) *Poultry - Production and Value 2011 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2012. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2011a) *Chicken and Eggs 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2011. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2011b) *Poultry - Production and Value 2010 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2011. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2010a) *Chicken and Eggs 2009 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2010. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2010b) *Poultry - Production and Value 2009 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2010. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2009a) *Chicken and Eggs 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. February 2009. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2009b) *Poultry - Production and Value 2008 Summary*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2009. Available online at:
[<http://www.nass.usda.gov/Publications/index.asp>](http://www.nass.usda.gov/Publications/index.asp).

USDA (2009c) *Chicken and Eggs – Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 2009. Available online at:
[<http://usda.mannlib.cornell.edu/usda/nass/SB980/sb1024.pdf>](http://usda.mannlib.cornell.edu/usda/nass/SB980/sb1024.pdf).

USDA (2009d) *Poultry Production and Value—Final Estimates 2003-2007*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. May 2009. Available online at:
[<http://usda.mannlib.cornell.edu/usda/nass/SB994/sb1028.pdf>](http://usda.mannlib.cornell.edu/usda/nass/SB994/sb1028.pdf).

USDA (2008) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture.

USDA (2004a) *Chicken and Eggs—Final Estimates 1998-2003*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at:
<http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (2004b) *Poultry Production and Value—Final Estimates 1998-2002*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. April 2004. Available online at:
<http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1999) *Poultry Production and Value—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1999. Available online at:
<http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1998) *Chicken and Eggs—Final Estimates 1994-97*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1998. Available online at:
<http://usda.mannlib.cornell.edu/reports/general/sb/>.

USDA (1996) *Agricultural Waste Management Field Handbook, National Engineering Handbook (NEH)*, Part 651. Natural Resources Conservation Service, U.S. Department of Agriculture. July 1996.

USDA (1995a) *Poultry Production and Value—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. March 1995. Available online at: <<http://usda.mannlib.cornell.edu/reports/general/sb/>>.

USDA (1995b) *Chicken and Eggs—Final Estimates 1988-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. December 1995. Available online at: <<http://usda.mannlib.cornell.edu/reports/general/sb/>>.

USDA (1994) *Sheep and Goats—Final Estimates 1989-1993*. National Agriculture Statistics Service, U.S. Department of Agriculture. Washington, D.C. January 31, 1994. Available online at: <<http://usda.mannlib.cornell.edu/reports/general/sb/>>.

USDA APHIS (2003) *Sheep 2001, Part I: Reference of Sheep Management in the United States, 2001 and Part IV: Baseline Reference of 2001 Sheep Feedlot Health and Management*. USDA-APHIS-VS. Fort Collins, CO. #N356.0702. Available online at <http://www.aphis.usda.gov/animal_health/nahms/sheep/index.shtml#sheep2001>.

USDA APHIS (2000) *Layers '99—Part II: References of 1999 Table Egg Layer Management in the U.S.* USDA-APHIS-VS. Fort Collins, CO. Available online at <http://www.aphis.usda.gov/animal_health/nahms/poultry/downloads/layers99/Layers99_dr_PartII.pdf>.

USDA APHIS (1996) *Swine '95: Grower/Finisher Part II: Reference of 1995 U.S. Grower/Finisher Health & Management Practices*. USDA-APHIS-VS. Fort Collins, CO. Available online at: <http://www.aphis.usda.gov/animal_health/nahms/swine/downloads/swine95/Swine95_dr_PartII.pdf>.

Wright, P. (2000) Personal Communication. Lee-Ann Tracy, ERG and Peter Wright, Cornell University, College of Agriculture and Life Sciences. June 23, 2000.

Rice Cultivation

Baicich, P. (2013) The Birds and Rice Connection. *Bird Watcher's Digest*. Available online at: <<http://www.usarice.com/doclib/194/6867.pdf>>.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Cheng, K., S.M. Ogle, W.J. Parton, G. Pan. (2014) "Simulating greenhouse gas mitigation potentials for Chinese croplands using the DAYCENT ecosystem model." *Global Change Biology* 20:948-962.

Cheng, K., S.M. Ogle, W.J. Parton and G. Pan. (2013) "Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model." *Ecological Modelling* 261-262:19-31.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N₂O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Deren, C. (2002) Personal Communication and Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

Fitzgerald, G.J., K. M. Scow & J. E. Hill (2000) "Fallow Season Straw and Rice Management Effects on Methane Emissions in California Rice." *Global biogeochemical cycles*, 14 (3), 767-776.

Fleskes, J.P., Perry, W.M., Petrik, K.L., Spell, R., and Reid, F. (2005) Change in area of winter-flood and dry rice in the northern Central Valley of California determined by satellite imagery. *California Fish and Game*, 91: 207-215.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Hardke, J.T., (2015) Trends in Arkansas rice production, 2014. B.R. Wells Arkansas Rice Research Studies 2014. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 626, Arkansas Agricultural Experiment Station, University of Arkansas.

Hardke, J. (2014) Personal Communication. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Kirsten Jaglo, ICF International. September 11, 2014.

- Hardke, J. (2013) Email correspondence. Dr. Jarrod Hardke, Rice Extension Agronomist at the University of Arkansas Rice Research and Extension Center and Cassandra Snow, ICF International. July 15, 2013.
- Hardke, J.T., and Wilson, C.E. Jr., (2013) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2012. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 609, Arkansas Agricultural Experiment Station, University of Arkansas.
- Hardke, J.T., and Wilson, C.E. Jr., (2014) Trends in Arkansas rice production, 2013. B.R. Wells Arkansas Rice Research Studies 2013. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 617, Arkansas Agricultural Experiment Station, University of Arkansas.
- Hollier, C. A. (ed), (1999) Louisiana rice production handbook. Louisiana State University Agricultural Center. LCES Publication Number 2321. 116 pp.
- Holzapfel-Pschorn, A., R. Conrad, and W. Seiler (1985) "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology*, 31:343-351.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- Kirstein, A. (2003 through 2004, 2006) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, FL and ICF International.
- Klosterboer, A. (1997, 1999 through 2003) Personal Communication. Arlen Klosterboer, retired Extension Agronomist, Texas A&M University and ICF International. July 7, 2003.
- Lindau, C.W. and P.K. Bollich (1993) "Methane Emissions from Louisiana First and Ratoon Crop Rice." *Soil Science*, 156:42-48.
- Linquist, B.A., M.A. Adviento-Borbe, C.M. Pittelkow, C.v. Kessel, et al. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research*, 135:10-21.
- Linscombe, S. (1999, 2001 through 2014) Email correspondence. Steve Linscombe, Professor with the Rice Research Station at Louisiana State University Agriculture Center and ICF International.
- LSU, (2015) Louisiana ratoon crop and conservation: Ratoon & Conservation Tillage Estimates. Louisiana State University, College of Agriculture AgCenter. Online at: www.lsuagcenter.com
- Miller, M.R., Garr, J.D., and Coates, P.S., (2010) Changes in the status of harvested rice fields in the Sacramento Valley, California: Implications for wintering waterfowl. *Wetlands*, 30: 939-947.
- Neue, H.U., R. Wassmann, H.K. Kludze, W. Bujun, and R.S. Lantin (1997) "Factors and processes controlling methane emissions from rice fields." *Nutrient Cycling in Agroecosystems* 49: 111-117.
- Ogle, S.M., S. Spencer, M. Hartman, L. Buendia, L. Stevens, D. du Toit, J. Witi (2016) "Developing national baseline GHG emissions and analyzing mitigation potentials for agriculture and forestry using an advanced national GHG inventory software system." In *Advances in Agricultural Systems Modeling 6, Synthesis and Modeling of Greenhouse Gas Emissions and Carbon Storage in Agricultural and Forestry Systems to Guide Mitigation and Adaptation*, S. Del Grosso, L.R. Ahuja and W.J. Parton (eds.), American Society of Agriculture, Crop Society of America and Soil Science Society of America, pp. 129-148.
- Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. (2007) "An empirically based approach for estimating uncertainty associated with modeling carbon sequestration in soils." *Ecological Modelling* 205:453-463.
- Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.
- Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

- Sass, R. L. (2001) CH₄ Emissions from Rice Agriculture. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 399-417. Available online at: <[http://www.ipcc-
nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf](http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_7_CH4_Rice_Agriculture.pdf)>.
- Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner (1990) "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles*, 4:47-68.
- Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner. (1994) "Methane emissions from rice fields: effect of soil texture." *Global Biogeochemical Cycles* 8:135-140.
- Schueneman, T. (1997, 1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International.
- Slaton, N. (1999 through 2001) Personal Communication. Nathan Slaton, Extension Agronomist—Rice, University of Arkansas Division of Agriculture Cooperative Extension Service and ICF International.
- Stansel, J. (2004 through 2005) Email correspondence. Dr. Jim Stansel, Resident Director and Professor Emeritus, Texas A&M University Agricultural Research and Extension Center and ICF International.
- TAMU, (2015) Texas Rice Crop Survey. Texas A&M AgriLIFE Research Center at Beaumont. Online at: <https://beaumont.tamu.edu/>
- Texas Agricultural Experiment Station (2007 through 2014) *Texas Rice Acreage by Variety*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System. Available online at: <<http://beaumont.tamu.edu/CropSurvey/CropSurveyReport.aspx>>.
- Texas Agricultural Experiment Station (2006) *2005 - Texas Rice Crop Statistics Report*. Agricultural Research and Extension Center, Texas Agricultural Experiment Station, Texas A&M University System, p. 8. Available online at: <http://beaumont.tamu.edu/eLibrary/TRRFReport_default.htm>.
- UCCE, 2015. Rice Production Manual. Revised (2015) University of California Cooperative Extension, Davis, in collaboration with the California Rice Research Board.
- USDA (2005 through 2014) *Crop Production Summary*. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu>>.
- USDA (2012) *Summary of USDA-ARS Research on the Interrelationship of Genetic and Cultural Management Factors That Impact Grain Arsenic Accumulation in Rice*. News and Events. Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://www.ars.usda.gov/is/pr/2012/120919.htm>>. September 2013.
- USDA (2003) *Field Crops, Final Estimates 1997-2002*. Statistical Bulletin No. 982. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu/usda/reports/general/sb/>>. September 2005.
- USDA (1998) *Field Crops Final Estimates 1992-1997*. Statistical Bulletin Number 947 a. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu/>>. July 2001.
- USDA (1994) *Field Crops Final Estimates 1987-1992*. Statistical Bulletin Number 896. National Agricultural Statistics Service, Agricultural Statistics Board, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu/>>. July 2001.
- USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.
- USDA-NRCS (2013) *Summary Report: 2010 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>
- van Bodegom, P.M., R. Wassmann, T.M. Metra-Corton (2001) "A process based model for methane emission predictions from flooded rice paddies." *Global Biogeochemical Cycles* 15: 247-263.

- Wang, J.J., S.K. Dodla, S. Viator, M. Kongchum, S. Harrison, S. D. Mudi, S. Liu, Z. Tian (2013) Agriculture Field Management Practices and Greenhouse Gas Emissions from Louisiana Soils. *Louisiana Agriculture*, Spring 2013: 8-9. Available online at: <<http://www.lsuagcenter.com/NR/rdonlyres/78D8B61A-96A8-49E1-B2EF-BA1D4CE4E698/93016/v56no2Spring2013.pdf>>.
- Wassmann, R. H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsil5, L.V. Buendia, and H. Rennenberg (2000a) Characterization of methane emissions from rice fields in Asia II. Differences among irrigated, rainfed, and deepwater rice." *Nutrient Cycling in Agroecosystems*, 58(1):13-22.
- Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, et al. (2000b) "Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs." *Nutrient Cycling in Agroecosystems*, 58(1):23-36.
- Way, M.O., McCauley, G.M., Zhou, X.G., Wilson, L.T., and Morace, B. (Eds.), (2014) 2014 Texas Rice Production Guidelines. Texas A&M AgriLIFE Research Center at Beaumont.
- Wilson, C. (2002 through 2007, 2009 through 2012) Personal Communication. Dr. Chuck Wilson, Rice Specialist at the University of Arkansas Cooperative Extension Service and ICF International.
- Wilson, C.E. Jr., and Branson, J.W., (2006) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2005. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 540, Arkansas Agricultural Experiment Station, University of Arkansas.
- Wilson, C.E. Jr., and Branson, J.W., (2005) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2004. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 529, Arkansas Agricultural Experiment Station, University of Arkansas.
- Wilson, C.E. Jr., Rumsick, S.K., and Mazzanti, R., (2010) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2009. Norman, R.J., and Moldenhauer, K.A.K., (Eds.). Research Series 581, Arkansas Agricultural Experiment Station, University of Arkansas.
- Wilson, C.E. Jr., Rumsick, S.K., Mazzanti, R., (2009) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies (2008) Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 571, Arkansas Agricultural Experiment Station, University of Arkansas.
- Wilson, C.E. Jr., and Rumsick, S.K., (2008) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2007. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 560, Arkansas Agricultural Experiment Station, University of Arkansas.
- Wilson, C.E. Jr., and Rumsick, S.K., (2007) Trends in Arkansas rice production. B.R. Wells Arkansas Rice Research Studies 2006. Norman, R.J., Meullenet, J.-F., and Moldenhauer, K.A.K., (Eds.). Research Series 550, Arkansas Agricultural Experiment Station, University of Arkansas.
- Yan, X., H. Akiyana, K. Yagi, and H. Akimoto (2009) "Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines." *Global Biogeochemical Cycles*, 23, DOI: 0.1029/2008GB003299.
- Young, M. (2013) Rice and Ducks. Ducks Unlimited, Memphis, TN. Available online at: <<http://www.ducks.org/conservation/farm-bill/rice-and-ducks---by-matt-young>>.

Agricultural Soil Management

AAPFCO (2008 through 2014) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

Bateman, E. J. and E. M. Baggs (2005) "Contributions of nitrification and denitrification to N₂O emissions from soils at different water-filled pore space." *Biology and Fertility of Soils* 41(6): 379-388.

Cibrowski, P. (1996) Personal Communication. Peter Cibrowski, Minnesota Pollution Control Agency and Heike Mainhardt, ICF Incorporated. July 29, 1996.

CTIC (2004) 2004 Crop Residue Management Survey. Conservation Technology Information Center. Available at <<http://www.ctic.purdue.edu/CRM/>>.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima (2005) "DAYCENT Model Analysis of Past and Contemporary Soil N₂O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research*, 83: 9-24. doi: 10.1016/j.still.2005.02.007.

Del Grosso, S.J., S.M. Ogle, W.J. Parton, and F.J. Breidt (2010) "Estimating Uncertainty in N₂O Emissions from U.S. Cropland Soils." *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

Del Grosso, S.J., W.J. Parton, C.A. Keough, and M. Reyes-Fox. (2011) Special features of the DayCent modeling package and additional procedures for parameterization, calibration, validation, and applications, in Methods of Introducing System Models into Agricultural Research, L.R. Ahuja and Liwang Ma, editors, p. 155-176, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI. USA.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Schaffer, M., L. Ma, S. Hansen, (eds.). Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press. Boca Raton, Florida. 303-332.

Del Grosso, S.J., T. Wirth, S.M. Ogle, W.J. Parton (2008) Estimating agricultural nitrous oxide emissions. EOS 89, 529-530.

Delgado, J.A., S.J. Del Grosso, and S.M. Ogle (2009) "15N isotopic crop residue cycling studies and modeling suggest that IPCC methodologies to assess residue contributions to N₂O-N emissions should be reevaluated." *Nutrient Cycling in Agroecosystems*, DOI 10.1007/s10705-009-9300-9.

Edmonds, L., N. Gollehon, R.L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaeffer (2003) "Costs Associated with Development and Implementation of Comprehensive Nutrient Management Plans." Part 1. Nutrient Management, Land Treatment, Manure and Wastewater Handling and Storage, and Recordkeeping. Natural Resource Conservation Service, U.S. Department of Agriculture.

EPA (2003) Clean Watersheds Needs Survey 2000—Report to Congress, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <<http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>>.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: <<http://biosolids.policy.net/relatives/18941.PDF>>.

EPA (1993) Federal Register. Part II. Standards for the Use and Disposal of Sewage Sludge; Final Rules. U.S. Environmental Protection Agency, 40 CFR Parts 257, 403, and 503.

Firestone, M. K., and E.A. Davidson, Ed. (1989) Microbiological basis of NO and N₂O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere. New York, John Wiley & Sons.

H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. *Bulletin of the American Meteorological Society* 87:343-360.

ILENR (1993) Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990. Office of Research and Planning, Illinois Department of Energy and Natural Resources. Springfield, IL.

IPCC (2013) *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. The Intergovernmental Panel on Climate Change. [T, Hiraishi, T. Krug, K. Tanabe, N. Srivastava, B. Jamsranjav, M. Fukuda and T. Troxler (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kessavalou, A., A.R. Mosier, J.W. Doran, R.A. Drijber, D.J. Lyon, and O. Heinemeyer (1998) "Fluxes of carbon dioxide, nitrogen oxide, and methane in grass sod and winter wheat -fallow tillage management." *Journal of Environmental Quality* 27: 1094-1104.

McFarland, M.J. (2001) *Biosolids Engineering*, New York: McGraw-Hill, p. 2.12.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. Mosier, A. R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami (1998) "Assessing and mitigating N₂O emissions from agricultural soils." *Climatic Change* 40: 7-38.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a, National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at:
[<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdf>](http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdf).

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCh1(99). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at:
[<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf>](http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf).

NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture. Available online at:
[<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txt>](http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txt).

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association, July 21, 2007.

Noller, J. (1996) Personal Communication. John Noller, Missouri Department of Natural Resources and Heike Mainhardt, ICF Incorporated. July 30, 1996.

Nusser, S.M., J.J. Goebel (1997) The national resources inventory: a long term monitoring programme. *Environmental and Ecological Statistics*, 4, 181-204.

Oregon Department of Energy (1995) Report on Reducing Oregon's Greenhouse Gas Emissions: Appendix D Inventory and Technical Discussion. Oregon Department of Energy. Salem, OR.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.

Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.

Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012. U.S Department of the Interior.

Scheer, C., S.J. Del Grosso, W.J. Parton, D.W. Rowlings, P.R. Grace (2013) Modeling Nitrous Oxide Emissions from Irrigated Agriculture: Testing DAYCENT with High Frequency Measurements, *Ecological Applications*, in press. Available online at: [<http://dx.doi.org/10.1890/13-0570.1>](http://dx.doi.org/10.1890/13-0570.1).

Soil Survey Staff (2011) State Soil Geographic (STATSGO) Database for State. Natural Resources Conservation Service, United States Department of Agriculture. Available online at:
[<http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html>](http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html).

Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.

TVA (1991 through 1992a, 1993 through 1994) Commercial Fertilizers. Tennessee Valley Authority, Muscle Shoals, AL.

USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: [<http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx>](http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx).

USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: <<http://www.ers.usda.gov/data/archive/93018/>>.

USDA-NASS (2014) Quick Stats. National Agricultural Statistics Service, United States Department of Agriculture, Washington, D.C. <<http://quickstats.nass.usda.gov/>>.

USDA-NRCS (2015) *Summary Report: 2012 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.

USDA-NRCS (2013) *Summary Report: 2010 National Resources Inventory*, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>

Vogelman, J.E., S.M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel (2001) "Completion of the 1990's National Land Cover Data Set for the conterminous United States." *Photogrammetric Engineering and Remote Sensing*, 67:650-662.

Wisconsin Department of Natural Resources (1993) Wisconsin Greenhouse Gas Emissions: Estimates for 1990. Bureau of Air Management, Wisconsin Department of Natural Resources, Madison, WI.

Field Burning of Agricultural Residues

Barnard, G., and L. Kristoferson (1985) *Agricultural Residues as Fuel in the Third World*. Earthscan Energy Information Programme and the Beijer Institute of the Royal Swedish Academy of Sciences. London, England.

Cantens, G. (2004 through 2005) Personal Communication. Janet Lewis, Assistant to Gaston Cantens, Vice President of Corporate Relations, Florida Crystals Company and ICF International.

Deren, C. (2002) Personal communication. Dr. Chris Deren, Everglades Research and Education Centre at the University of Florida and Caren Mintz, ICF International. August 15, 2002.

EPA (1994) *International Anthropogenic Methane Emissions: Estimates for 1990, Report to Congress*. EPA 230-R-93-010. Office of Policy Planning and Evaluation, U.S. Environmental Protection Agency, Washington, D.C.

Gonzalez, R. (2007 through 2014) Email correspondence. Rene Gonzalez, Plant Manager, Sem-Chi Rice Company and ICF International.

Huang, Y., W. Zhang, W. Sun, and X. Zheng (2007) "Net Primary Production of Chinese Croplands from 1950 to 1999." *Ecological Applications*, 17(3):692-701.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency, Paris, France.

Kinoshita, C.M. (1988) "Composition and processing of burned and unburned cane in Hawaii." *Intl. Sugar Jnl.* 90:1070, 34-37.

Kirstein, A. (2003 through 2004) Personal Communication. Arthur Kirstein, Coordinator, Agricultural Economic Development Program, Palm Beach County Cooperative Extension Service, Florida and ICF International.

Lachnicht, S.L., P.F. Hendrix, R.L. Potter, D.C. Coleman, and D.A. Crossley Jr. (2004) "Winter decomposition of transgenic cotton residue in conventional-till and no-till systems." *Applied Soil Ecology*, 27:135-142.

Lee, D. (2003 through 2007) Email correspondence. Danny Lee, OK Farm Service Agency and ICF International.

McCarty, J.L. (2011) "Remote Sensing-Based Estimates of Annual and Seasonal Emissions from Crop Residue Burning in the Contiguous United States." *Journal of the Air & Waste Management Association*, 61:1,22-34, DOI: 10.3155/1047-3289.61.1.22.

McCarty, J.L. (2010) Agricultural Residue Burning in the Contiguous United States by Crop Type and State. Geographic Information Systems (GIS) Data provided to the EPA Climate Change Division by George Pouliot, Atmospheric Modeling and Analysis Division, EPA. Dr. McCarty's research was supported by the NRI Air Quality Program of the Cooperative State Research, Education, and Extension Service, USDA, under Agreement No. 20063511216669 and the NASA Earth System Science Fellowship.

McCarty, J.L. (2009) *Seasonal and Interannual Variability of Emissions from Crop Residue Burning in the Contiguous United States*. Dissertation. University of Maryland, College Park.

Murphy, W.J. (1993) "Tables for weights and measurement: crops". *Extension publications. (University of Missouri Extension)*. Available online at: <<http://extension.missouri.edu/publications/DisplayPub.aspx?P=G4020>>.

Schueneman, T. (1999 through 2001) Personal Communication. Tom Schueneman, Agricultural Extension Agent, Palm Beach County, FL and ICF International. July 30, 2001. Schueneman, T.J. and C.W. Deren (2002) "An Overview of the Florida Rice Industry." SS-AGR-77, Agronomy Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Revised November 2002.

Strehler, A., and W. Stützle (1987) "Biomass Residues." In Hall, D.O. and Overend, R.P. (eds.). *Biomass*. John Wiley and Sons, Ltd. Chichester, UK.

Turn, S.Q., B.M. Jenkins, J.C. Chow, L.C. Pritchett, D. Campbell, T. Cahill, and S.A. Whalen (1997) "Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels." *Journal of Geophysical Research* 102(D3):3683-3699.

USDA (2013) 2010 National Resources Inventory, Natural Resources Conservation Service, Washington DC and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa.

USDA (2015) Quick Stats: U.S. & All States Data; Crops; Production and Area Harvested; 1990 - 2014. National Agricultural Statistics Service, U.S. Department of Agriculture. Washington, D.C. U.S. Department of Agriculture, National Agricultural Statistics Service. Washington, D.C., Available online at: <<http://quickstats.nass.usda.gov/>>.

Land Use, Land-Use Change, and Forestry

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

UNFCCC (2013) *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*. Available online at: <<http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf>>.

Representation of the U.S. Land Base

Alaska Department of Natural Resources (2006) Alaska Infrastructure 1:63,360. Available online at: <<http://dnr.alaska.gov/SpatialUtility/SUC?cmd=extract&layerid=75>>.

Alaska Interagency Fire Management Council (1998) Alaska Interagency Wildland Fire Management Plan. Available online at: <<http://agdc.usgs.gov/data/blm/fire/index.html>>.

Alaska Oil and Gas Conservation Commission (2009) Oil and Gas Information System. Available online at: <<http://doa.alaska.gov/ogc/publicdb.html>>.

EIA (2011) Coal Production and Preparation Report Shapefile. Available online at: <<http://www.eia.gov/state/notes-sources.cfm#maps>>.

ESRI (2008) ESRI Data & Maps. Redlands, CA: Environmental Systems Research Institute. [CD-ROM]

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and J. Wickham. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N. Herold, A. McKerrow, J.N. VanDriel and J. Wickham. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States, Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

IPCC (2010) Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals. [Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, (eds.)]. Institute for Global Environmental Studies, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. (2013) A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment*, 132: 159-175.

NOAA Coastal Change Analysis Program (C-CAP) Regional Land Cover Database. Data collected 1995-present Charleston, SC: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center. Data accessed at <www.csc.noaa.gov/landcover>.

Nusser, S.M. and J.J. Goebel (1997) "The national resources inventory: a long-term multi-resource monitoring programme." *Environmental and Ecological Statistics* 4:181-204.

Smith, W.B., P.D. Miles, C.H. Perry, and S.A. Pugh (2009) *Forest Resources of the United States, 2007*. Gen. Tech. Rep. WO-78. U.S. Department of Agriculture Forest Service, Washington, D.C.

U.S. Census Bureau (2010) Topologically Integrated Geographic Encoding and Referencing (TIGER) system shapefiles. U.S. Census Bureau, Washington, D.C. Available online at: <<http://www.census.gov/geo/www/tiger>>.

U.S. Department of Agriculture (2014) County Data - Livestock, 1990-2014. U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, D.C.

U.S. Department of Interior (2005) *Federal Lands of the United States*. National Atlas of the United States, U.S. Department of the Interior, Washington D.C. Available online at: <<http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound>>.

United States Geological Survey (USGS), Gap Analysis Program (2012) Protected Areas Database of the United States (PADUS), version 1.3 Combined Feature Class. November 2012.

USGS (2012) Alaska Resource Data File. Available online at: <<http://ardf.wr.usgs.gov/>>.

USGS (2005) Active Mines and Mineral Processing Plants in the United States in 2003. U.S. Geological Survey, Reston, VA.

Forest Land Remaining Forest Land: Changes in Forest Carbon Stocks

AF&PA (2006a and earlier) Statistical roundup. (Monthly). Washington, D.C. American Forest & Paper Association.

AF&PA (2006b and earlier) Statistics of paper, paperboard and wood pulp. Washington, D.C. American Forest & Paper Association.

Amichev, B.Y. and J.M. Galbraith (2004) "A Revised Methodology for Estimation of Forest Soil Carbon from Spatial Soils and Forest Inventory Data Sets." *Environmental Management* 33(Suppl. 1):S74-S86.

Bechtold, W.A.; Patterson, P.L. (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 85 p.

Birdsey, R. (1996) "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In R.N. Sampson and D. Hair, (eds.). *Forest and Global Change, Volume 2: Forest Management Opportunities for Mitigating Carbon Emissions*. American Forests. Washington, D.C., 1-26 and 261-379 (appendices 262 and 263).

- Coulston, J.W., Wear, D.N., and Vose, J.M. (2015) Complex forest dynamics indicate potential for slowing carbon accumulation in the southeastern United States. *Scientific Reports.* 5: 8002.
- Domke, G.M., J.E. Smith, and C.W. Woodall. (2011) Accounting for density reduction and structural loss in standing dead trees: Implications for forest biomass and carbon stock estimates in the United States. *Carbon Balance and Management.* 6:14.
- Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E. (2012) Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. *Forest Ecology and Management.* 270: 108-116
- Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., and Smith, J.E. (2016) A framework for estimating litter carbon stocks in forests of the United States. *Science of the Total Environment* 557–558: 469–478.
- Domke, G.M., Woodall, C.W., Walters, B.F., Smith, J.E. (2013) From models to measurements: comparing down dead wood carbon stock estimates in the U.S. forest inventory. *PLoS ONE* 8(3): e59949.
- Domke, G.M., Perry, C.H., Walters, B.F., Nave, L.E., Woodall, C.W., Swanston, C.W. (In Preparation) Estimating soil organic carbon in forest land of the United States. Intended outlet: *Ecological Applications.*
- EPA (2006) *Municipal solid waste in the United States: 2005 Facts and figures.* Office of Solid Waste, U.S. Environmental Protection Agency. Washington, D.C. (5306P) EPA530-R-06-011. Available online at: <<http://www.epa.gov/msw/msw99.htm>>.
- Frayer, W.E., and G.M. Furnival (1999) “Forest Survey Sampling Designs: A History.” *Journal of Forestry* 97(12): 4-10.
- Freed, R. (2004) Open-dump and Landfill timeline spreadsheet (unpublished). ICF International. Washington, D.C.
- Hair, D. (1958) “Historical forestry statistics of the United States.” *Statistical Bull.* 228. U.S. Department of Agriculture Forest Service, Washington, D.C.
- Hair, D. and A.H. Ulrich (1963) The Demand and price situation for forest products – 1963. U.S. Department of Agriculture Forest Service, Misc Publication No. 953. Washington, D.C.
- Harmon, M.E., C.W. Woodall, B. Fasth, J. Sexton, M. Yatkov. (2011) Differences between standing and downed dead tree wood density reduction factors: A comparison across decay classes and tree species. Res. Paper. NRS-15. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 40 p.
- Howard, J. L. (Forthcoming) *U.S. timber production, trade, consumption, and price statistics 1965 to 2013.* Res. Pap. FPL-RP-XXX. Madison, WI: USDA, Forest Service, Forest Products Laboratory.
- Howard, J. L. (2007) *U.S. timber production, trade, consumption, and price statistics 1965 to 2005.* Res. Pap. FPL-RP-637. Madison, WI: USDA, Forest Service, Forest Products Laboratory.
- Howard, J. L. (2003) *U.S. timber production, trade, consumption, and price statistics 1965 to 2002.* Res. Pap. FPL-RP-615. Madison, WI: USDA, Forest Service, Forest Products Laboratory. Available online at: <<http://www.fpl.fs.fed.us/documents/fplrp/fplrp615/fplrp615.pdf>>.
- Ince, P.J., Kramp, A.D., Skog, K.E., Spelter, H.N. and Wear, D.N., (2011) US Forest Products Module: a technical document supporting the forest service 2010 RPA assessment. Research Paper-Forest Products Laboratory, USDA Forest Service, (FPL-RP-662).
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands.* [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T.G. (eds.)]. Switzerland.
- IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen,

M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey (2003) "National-scale biomass estimators for United States tree species." *Forest Science* 49(1):12-35.

Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., deB Richter Jr., D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F. (2014) Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of the Total Environment*, 468, 376-383.

Ogle, S.M., Woodall, C.W., Swan, A., Smith, J.E., Wirth, T. In preparation. Determining the Managed Land Base for Delineating Carbon Sources and Sinks in the United States. *Environmental Science and Policy*.

O'Neill, K.P., Amacher, M.C., Perry, C.H. (2005) Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: US Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. (2014) Forest Resources of the United States, 2012. Gen. Tech. Rep. WO-91. Washington, D.C. U.S. Department of Agriculture, Forest Service, Washington Office. 218 p.

Perry, C.H., C.W. Woodall, and M. Schoeneberger (2005) Inventorying trees in agricultural landscapes: towards an accounting of "working trees". In: "Moving Agroforestry into the Mainstream." *Proc. 9th N. Am. Agroforestry Conf.*, Brooks, K.N. and Folliott, P.F. (eds.). 12-15 June 2005, Rochester, MN [CD-ROM]. Dept. of Forest Resources, Univ. Minnesota, St. Paul, MN, 12 p. Available online at: <<http://cinram.umn.edu/afta2005/>>. (verified 23 Sept 2006).

Russell, M.B.; D'Amato, A.W.; Schulz, B.K.; Woodall, C.W.; Domke, G.M.; Bradford, J.B. (2014) Quantifying understory vegetation in the U.S. Lake States: a proposed framework to inform regional forest carbon stocks. *Forestry*. 87: 629-638.

Russell, M.B.; Domke, G.M.; Woodall, C.W.; D'Amato, A.W. (2015) Comparisons of allometric and climate-derived estimates of tree coarse root carbon in forests of the United States. *Carbon Balance and Management*. 10: 20.

Skog, K.E. (2008) Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal* 58:56-72.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. (2006) *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States*. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, W. B., P. D. Miles, C. H. Perry, and S. A. Pugh (2009) *Forest Resources of the United States, 2007*. General Technical Report WO-78, U.S. Department of Agriculture Forest Service, Washington Office.

Steer, Henry B. (1948) *Lumber production in the United States*. Misc. Pub. 669, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, Alice (1985) *U.S. Timber Production, Trade, Consumption, and Price Statistics 1950-1985*. Misc. Pub. 1453, U.S. Department of Agriculture Forest Service. Washington, D.C.

Ulrich, A.H. (1989) *U.S. Timber Production, Trade, Consumption, and Price Statistics, 1950-1987*. USDA Miscellaneous Publication No. 1471, U.S. Department of Agriculture Forest Service. Washington, D.C, 77.

United Nations Framework Convention on Climate Change. (2013) Report on the individual review of the inventory submission of the United States of America submitted in 2012. FCCC/ARR/2012/USA. 42 p.

USDA Forest Service (2015a) Forest Inventory and Analysis National Program: Program Features. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <<http://fia.fs.fed.us/program-features/>>. Accessed 17 September 2015.

USDA Forest Service. (2015b) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <<http://apps.fs.fed.us/fiadb-downloads/datamart.html>>. Accessed on 17 September 2015.

USDA Forest Service. (2015c) Forest Inventory and Analysis National Program, FIA library: Field Guides, Methods and Procedures. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <<http://www.fia.fs.fed.us/library/field-guides-methods-proc/>>. Accessed on 17 September 2015.

USDA Forest Service (2015d) Forest Inventory and Analysis National Program, FIA library: Database Documentation. U.S. Department of Agriculture, Forest Service, Washington Office. Available online at: <<http://fia.fs.fed.us/library/database-documentation/>>. Accessed on 17 September 2015.

U.S. Census Bureau (1976) *Historical Statistics of the United States, Colonial Times to 1970, Vol. 1*. Washington, D.C.

Wear, D.N., Coulston, J.W. (2015) From sink to source: Regional variation in U.S. forest carbon futures. *Scientific Reports*. 5: 16518.

Westfall, J.A., Woodall, C.W., Hatfield, M.A. (2013) A statistical power analysis of woody carbon flux from forest inventory data. *Climatic Change*. 118: 919-931.

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The US Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B., Will-Wolf, S. (2011b) "Status and future of the forest health indicators program of the United States." *Environmental Monitoring and Assessment*. 177: 419-436.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011a) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Woodall, C.W., and V.J. Monleon (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 68 p.

Woodall, C.W., Walters, B.F., Oswalt, S.N., Domke, G.M., Toney, C., Gray, A.N. (2013) Biomass and carbon attributes of downed woody materials in forests of the United States. *Forest Ecology and Management* 305: 48-59.

Woodall, C.W., Walters, B.F., Coulston, J.W., D'Amato, A.W., Domke, G.M., Russell, M.B., Sowers, P.A. (2015b) Monitoring network confirms land use change is a substantial component of the forest carbon sink in the eastern United States. *Scientific Reports*. 5: 17028.

Forest Land Remaining Forest Land: Non-CO₂ Emissions from Forest Fires

deVries, R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Dwyer, J.F., D.J. Nowak, M.H. Noble, and S.M. Sisinni (2000) Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Nowak, D.J. (2011) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nikhil Nadkarni, ICF International. January 4, 2011.

Nowak, D.J. (2009) E-mail correspondence regarding new data for Chicago's urban forest. David Nowak, USDA Forest Service to Nikhil Nadkarni, ICF International. October 7, 2009.

Nowak, D.J. (2007a) "New York City's Urban Forest." USDA Forest Service. Newtown Square, PA, February 2007.

Nowak, D.J. (2007b) E-mail correspondence regarding revised sequestration values and standard errors for sequestration values. David Nowak, USDA Forest Service to Susan Asam, ICF International. October 31, 2007.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.). General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (1986) "Silvics of an Urban Tree Species: Norway Maple (*Acer platanoides* L.)." M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J., Buckelew-Cumming, A., Twardus, D., Hoehn, R., and Mielke, M. (2007) National Forest Health Monitoring Program, Monitoring Urban Forests in Indiana: Pilot Study 2002, Part 2: Statewide Estimates Using the UFORE Model. Northeastern Area Report. NA-FR-01e07, p. 13.

Nowak, D.J. and D.E. Crane (2002) "Carbon Storage and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116(3):381–389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., and E.J. Greenfield (2012) Tree and impervious cover in the United States. *Journal of Landscape and Urban Planning* (107) pp. 21-30.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. *Environmental Pollution* 178: 229-236. March 12, 2013.

Nowak, D.J., J.T. Walton, L.G. Kaya, and J.F. Dwyer (2005) "The Increasing Influence of Urban Environments on U.S. Forest Management." *Journal of Forestry* 103(8):377–382.

Ruefenacht, B., M.V. Finco, M.D. Nelson, R. Czaplewski, E.H. Helmer, J.A. Blackard, G.R. Holden, A.J. Lister, D. Salajanu, D. Weyermann, K. Winterberger (2008) Conterminous U.S. and Alaska Forest Type Mapping Using Forest Inventory and Analysis. USDA Forest Service - Forest Inventory and Analysis Program & Remote Sensing Applications Center. Available online at: <http://data.fs.usda.gov/geodata/rastergateway/forest_type/>. Accessed 8 September 2015.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Census Bureau (2012) "A national 2010 urban area file containing a list of all urbanized areas and urban clusters (including Puerto Rico and the Island Areas) sorted by UACE code." U.S. Census Bureau, Geography Division.

Veraverbeke, S., B.M. Rogers, and J.T. Randerson. (2015) Daily burned area and carbon emissions from boreal fires in Alaska. *Biogeosciences*, 12:3579–3601.

Forest Land Remaining Forest Land: N₂O Fluxes from Soils

Albaugh, T.J., Allen, H.L., Fox, T.R. (2007) Historical Patterns of Forest Fertilization in the Southeastern United States from 1969 to 2004. *Southern Journal of Applied Forestry*, 31, 129-137(9).

Binkley, D. (2004) Email correspondence regarding the 95% CI for area estimates of southern pine plantations receiving N fertilizer ($\pm 20\%$) and the rate applied for areas receiving N fertilizer (100 to 200 pounds/acre). Dan Binkley, Department of Forest, Rangeland, and Watershed Stewardship, Colorado State University and Stephen Del Grosso, Natural Resource Ecology Laboratory, Colorado State University. September 19, 2004.

Binkley, D., R. Carter, and H.L. Allen (1995) Nitrogen Fertilization Practices in Forestry. In: *Nitrogen Fertilization in the Environment*, P.E. Bacon (ed.), Marcel Decker, Inc., New York.

Briggs, D. (2007) *Management Practices on Pacific Northwest West-Side Industrial Forest Lands, 1991-2005: With Projections to 2010*. Stand Management Cooperative, SMC Working Paper Number 6, College of Forest Resources, University of Washington, Seattle.

Fox, T.R., H. L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson (2007) Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. *Southern Journal of Applied Forestry*, 31, 5-11.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

USDA Forest Service (2001) *U.S. Forest Facts and Historical Trends*. FS-696. U.S. Department of Agriculture Forest Service, Washington, D.C. Available online at: <<http://www.fia.fs.fed.us/library/ForestFactsMetric.pdf>>.

Land Converted to Forest Land

Birdsey, R., Pregitzer, K., Lucier, A. (2006) Forest carbon management in the United States: 1600-2100. *Journal of Environmental Quality*, 35: 1461-1469.

Domke, G.M., Perry, C.H., Walters, B.F., Nave, L.E., Woodall, C.W., Swanston, C.W. (In Preparation) Estimating of soil organic carbon in forest land of the United States. Intended outlet: Ecological Applications.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme*, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Ogle, S.M., F.J. Breidt, and K. Paustian. (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

USDA-NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.

USDA-NRCS (2009) Summary Report: 2007 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usdagov?technical/NRI/2007/2007_NRI_Summary.pdf>

Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015a) The US Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.

Cropland Remaining Cropland: Mineral and Organic Soil Carbon Stock Changes

Armentano, T. V., and E.S. Menges (1986). Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* 74: 755-774.

Brady, N.C. and R.R. Weil (1999) *The Nature and Properties of Soils*. Prentice Hall. Upper Saddle River, NJ, 881.
Conant, R. T., K. Paustian, and E.T. Elliott (2001). "Grassland management and conversion into grassland: effects on soil carbon." *Ecological Applications* 11: 343-355.

CTIC (2004) National Crop Residue Management Survey: 1989-2004. Conservation Technology Information Center, Purdue University, Available online at: <<http://www.ctic.purdue.edu/CRM/>>

Daly, C., R.P. Neilson, and D.L. Phillips (1994) "A Statistical-Topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain." *Journal of Applied Meteorology* 33:140-158.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: *Understanding Greenhouse Gas Emissions from Agricultural Management*, L. Guo, A. Gunasekara, L. McConnell (eds.). American Chemical Society, Washington, D.C.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: <<http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>>.

Euliss, N., and R. Gleason (2002) Personal communication regarding wetland restoration factor estimates and restoration activity data. Ned Euliss and Robert Gleason of the U.S. Geological Survey, Jamestown, ND, to Stephen Ogle of the National Resource Ecology Laboratory, Fort Collins, CO. August 2002.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman, et al., eds. August 13, 2004. Available online at: <<http://www.ipcc-nngip.iges.or.jp/public/gpglulucf/gpglulucf.htm>>.

McGill, W.B., and C.V. Cole (1981) Comparative aspects of cycling of organic C, N, S and P through soil organic matter. *Geoderma* 26:267-286.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi (2006) North American regional reanalysis. *Bulletin of the American Meteorological Society* 87:343-360.

NASS (2004) Agricultural Chemical Usage: 2003 Field Crops Summary. Report AgCh1(04)a. National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agcs0504.pdfH>>.

NASS (1999) Agricultural Chemical Usage: 1998 Field Crops Summary. Report AgCH1(99). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, DC. Available online at: <<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0599.pdf>>.

NASS (1992) Agricultural Chemical Usage: 1991 Field Crops Summary. Report AgCh1(92). National Agricultural Statistics Service, U.S. Department of Agriculture, Washington, D.C. Available online at: <<http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/agch0392.txtH>>.

NRCS (1999) Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd Edition. Agricultural Handbook Number 436, Natural Resources Conservation Service, U.S. Department of Agriculture, Washington, D.C.

NRCS (1997) "National Soil Survey Laboratory Characterization Data," Digital Data, Natural Resources Conservation Service, U.S. Department of Agriculture. Lincoln, NE.

NRCS (1981) Land Resource Regions and Major Land Resource Areas of the United States, USDA Agriculture Handbook 296, United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Cente., Lincoln, NE, pp. 156.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian (2007) "Empirically-Based Uncertainty Associated with Modeling Carbon Sequestration Rates in Soils." *Ecological Modeling* 205:453-463.

Ogle, S.M., F.J. Breidt, and K. Paustian (2006) "Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments." *Global Change Biology* 12:516-523.

Ogle, S. M., et al. (2005) "Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions." *Biogeochemistry* 72: 87-121.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Ogle, S., M. Eve, M. Sperrow, F.J. Breidt, and K. Paustian (2002) Agricultural Soil C Emissions, 1990-2001: Documentation to Accompany EPA Inventory Tables. Natural Resources Ecology Laboratory, Fort Collins, CO. Provided in an e-mail from Stephen Ogle, NREL to Barbara Braatz, ICF International. September 23, 2002

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Paustian, K., et al. (1997a). "Agricultural soils as a sink to mitigate CO₂ emissions." *Soil Use and Management* 13: 230-244.

- Paustian, K., et al. (1997b) Management controls on soil carbon. In *Soil organic matter in temperate agroecosystems: long-term experiments in North America* (Paul E.A., K. Paustian, and C.V. Cole, eds.). Boca Raton, CRC Press, pp. 15-49.
- Potter, C. S., J.T. Randerson, C.B. Fields, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster (1993) "Terrestrial ecosystem production: a process model based on global satellite and surface data." *Global Biogeochemical Cycles* 7:811-841.
- Potter, C., S. Klooster, A. Huete, and V. Genovese (2007) Terrestrial carbon sinks for the United States predicted from MODIS satellite data and ecosystem modeling. *Earth Interactions* 11, Article No. 13, DOI 10.1175/EI228.1.
- PRISM Climate Group (2015) *PRISM Climate Data*. Oregon State University. July 24, 2015. Available online at: <<http://prism.oregonstate.edu>>.
- Soil Survey Staff (2015) State Soil Geographic (STATSGO) Database for State. Natural Resources Conservation Service, United States Department of Agriculture. Available online at: <<http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html>>.
- Towery, D. (2001) Personal Communication. Dan Towery regarding adjustments to the CTIC (1998) tillage data to reflect long-term trends, Conservation Technology Information Center, West Lafayette, IN, and Marlen Eve, National Resource Ecology Laboratory, Fort Collins, CO. February 2001.
- USDA-ERS (2011) Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices: Tailored Reports. Available online at: <<http://ers.usda.gov/Data/ARMS/CropOverview.htm>>.
- USDA-ERS (1997) Cropping Practices Survey Data—1995. Economic Research Service, United States Department of Agriculture. Available online at: <<http://www.ers.usda.gov/data/archive/93018/>>.
- USDA-FSA (2014) Conservation Reserve Program Monthly Summary – September 2014. U.S. Department of Agriculture, Farm Service Agency, Washington, D.C. Available online at: <<https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/summarysept2014.pdf>>.
- USDA-NRCS (2000) Digital Data and Summary Report: 1997 National Resources Inventory. Revised December 2000. Resources Inventory Division, Natural Resources Conservation Service, United States Department of Agriculture, Beltsville, MD.
- USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.
- USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.

Cropland Remaining Cropland: Liming

- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- Tepordei, V.V. (1997 through 2006) "Crushed Stone," In *Minerals Yearbook*. U.S. Department of the Interior/U.S. Geological Survey. Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>.
- Tepordei, V.V. (2003b) Personal communication. Valentin Tepordei, U.S. Geological Survey and ICF Consulting, August 18, 2003.
- Tepordei, V.V. (1996) "Crushed Stone," In *Minerals Yearbook 1994*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2000.
- Tepordei, V.V. (1995) "Crushed Stone," In *Minerals Yearbook 1993*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1107–1147.

Tepordei, V. V. (1994) "Crushed Stone," In *Minerals Yearbook 1992*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1279-1303.

Tepordei, V.V. (1993) "Crushed Stone," In *Minerals Yearbook 1991*. U.S. Department of the Interior/Bureau of Mines, Washington, D.C. pp. 1469-1511.

USGS (2015) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2015*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2014) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2014*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2013) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2013*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2012) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2012*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2011) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2011*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2010) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2010*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2009) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2009*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2008) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2008*, U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

USGS (2007) *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2007*. U.S. Geological Survey, Reston, VA. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis).

West, T.O. (2008) Email correspondence. Tristram West, Environmental Sciences Division, Oak Ridge National Laboratory, U.S. Department of Energy and Nikhil Nadkarni, ICF International on suitability of liming emission factor for the entire United States. June 9, 2008.

West, T.O., and A.C. McBride (2005) "The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions," *Agricultural Ecosystems & Environment* 108:145-154.

Willett, J.C. (2015) "Crushed Stone," In *Minerals Yearbook 2013*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis). Accessed September 2015.

Willett, J.C. (2014) "Crushed Stone," In *Minerals Yearbook 2012*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis). Accessed September 2014.

Willett, J.C. (2013a) "Crushed Stone," In *Minerals Yearbook 2011*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at:
[<http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>](http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis). Accessed May 2013.

Willett, J.C. (2013b) Personal Communication. Jason Willet, U.S. Geological Survey and ICF International. September 9, 2013.

- Willett, J.C. (2011a) "Crushed Stone," In *Minerals Yearbook 2009*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2011.
- Willett, J.C. (2011b) "Crushed Stone," In *Minerals Yearbook 2010*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed September 2012.
- Willett, J.C. (2010) "Crushed Stone," In *Minerals Yearbook 2008*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2010.
- Willett, J.C. (2009) "Crushed Stone," In *Minerals Yearbook 2007*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2009.
- Willett, J.C. (2007a) "Crushed Stone," In *Minerals Yearbook 2005*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2007.
- Willett, J.C. (2007b) "Crushed Stone," In *Minerals Yearbook 2006*. U.S. Department of the Interior/U.S. Geological Survey, Washington, D.C. Available online at: <http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/index.html#mis>. Accessed August 2008.

Cropland Remaining Cropland: Urea Fertilization

AAPFCO (2008 through 2014) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Missouri. Columbia, MO.

AAPFCO (1995 through 2000a, 2002 through 2007) Commercial Fertilizers. Association of American Plant Food Control Officials. University of Kentucky. Lexington, KY.

AAPFCO (2000b) *1999-2000 Commercial Fertilizers Data, ASCII files*. Available from David Terry, Secretary, AAPFCO.

EPA (2000) Preliminary Data Summary: Airport Deicing Operations (Revised). EPA-821-R-00-016. August 2000.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Itle, C. (2009) Email correspondence. Cortney Itle, ERG and Tom Wirth, U.S. Environmental Protection Agency on the amount of urea used in aircraft deicing. January 7, 2009.

Terry, D. (2007) Email correspondence. David Terry, Fertilizer Regulatory program, University of Kentucky and David Berv, ICF International. September 7, 2007.

TVA (1991 through 1994) *Commercial Fertilizers*. Tennessee Valley Authority, Muscle Shoals, AL.

TVA (1992b) Fertilizer Summary Data 1992. Tennessee Valley Authority, Muscle Shoals, AL.

Land Converted to Cropland

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In *Modeling Carbon and Nitrogen Dynamics for Soil Management*, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: *Understanding Greenhouse Gas Emissions from Agricultural Management* (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354. Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO₂ to the atmosphere." *Ecological Monographs* 53: 235-262.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Schimel, D.S. (1995) "Terrestrial ecosystems and the carbon cycle." *Global Change Biology* 1: 77-91.

Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.

USDA Forest Service (2015) Forest Inventory and Analysis National Program: FIA Data Mart. U.S. Department of Agriculture Forest Service. Washington, D.C. Available online at: <<http://apps.fs.fed.us/fiadownload/datamart.html>>. Accessed on 17 September 2015.

USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.

USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C. and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.

Woodall, C.W., L.S. Heath, G.M. Domke, and M.C. Nichols (2011) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p.

Grassland Remaining Grassland

Del Grosso, S.J., S.M. Ogle, W.J. Parton (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas

Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell. Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management, Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Edmonds, L., R. L. Kellogg, B. Kintzer, L. Knight, C. Lander, J. Lemunyon, D. Meyer, D.C. Moffitt, and J. Schaefer (2003) "Costs associated with development and implementation of Comprehensive Nutrient Management Plans." Part I—Nutrient management, land treatment, manure and wastewater handling and storage, and recordkeeping. Natural Resources Conservation Service, U.S. Department of Agriculture. Available online at: <<http://www.nrcs.usda.gov/technical/land/pubs/cnmp1.html>>.

EPA (1999) Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste, U.S. Environmental Protection Agency. Available online at: <<http://biosolids.policy.net/relatives/18941.PDF>>.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345-354

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon (2000) Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. U.S. Department of Agriculture, Washington, D.C. Publication number nps00-0579.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

NEBRA (2007) A National Biosolids Regulation, Quality, End Use & Disposal Survey. North East Biosolids and Residuals Association. July 21, 2007.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.

United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: <http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html>.

USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.

USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.

Land Converted to Grassland

Del Grosso, S.J., S.M. Ogle, W.J. Parton. (2011) Soil organic matter cycling and greenhouse gas accounting methodologies, Chapter 1, pp 3-13 DOI: 10.1021/bk-2011-1072.ch001. In: Understanding Greenhouse Gas Emissions from Agricultural Management (L. Guo, A. Gunasekara, L. McConnell, Eds.), American Chemical Society, Washington, D.C.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, J. Brenner, D.S. Ojima, and D.S. Schimel (2001) "Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model." In Modeling Carbon and Nitrogen Dynamics for Soil Management (Schaffer, M., L. Ma, S. Hansen, (eds.). CRC Press, Boca Raton, Florida, pp. 303-332.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J. (2011) Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J. (2007) Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing*, Vol. 73, No. 4, pp 337-341.

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K. (2015) Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345-354.

Houghton, R.A., et al. (1983) "Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO₂ to the atmosphere." *Ecological Monographs* 53: 235-262.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, [H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2010) "Scale and uncertainty in modeled soil organic carbon stock changes for U.S. croplands using a process-based model." *Global Change Biology* 16:810-820.

Ogle, S.M., M.D. Eve, F.J. Breidt, and K. Paustian (2003) "Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agroecosystems between 1982 and 1997." *Global Change Biology* 9:1521-1542.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) "A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management," in Quantitative Modeling of Soil Forming Processes. Special Publication 39, *Soil Science Society of America*, Madison, WI, 147-167.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

- Parton, W.J., J.W.B. Stewart, C.V. Cole (1988) "Dynamics of C, N, P, and S in grassland soils: a model." *Biogeochemistry* 5:109-131.
- Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) "DAYCENT: Its Land Surface Submodel: Description and Testing". *Glob. Planet. Chang.* 19: 35-48.
- Schimel, D.S. (1995) "Terrestrial ecosystems and the carbon cycle." *Global Change Biology* 1: 77-91.
- Tubiello, F. N., et al. (2015) "The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012." *Global Change Biology* 21:2655-2660.
- United States Bureau of Land Management (BLM) (2014) *Rangeland Inventory, Monitoring, and Evaluation Reports*. Bureau of Land Management. U.S. Department of the Interior. Available online at: <http://www.blm.gov/wo/st/en/prog/more/rangeland_management/rangeland_inventory.html>.
- USDA-NRCS (2015) Summary Report: 2012 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C., and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf>.
- USDA-NRCS (2013) Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service, Washington, D.C. and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. Available online at: <http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf>.
- ## Wetlands Remaining Wetlands: CO₂, CH₄, and N₂O Emissions from Peatlands Remaining Peatlands
- Apodaca, L. (2011) Email correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. November.
- Apodaca, L. (2008) E-mail correspondence. Lori Apodaca, Peat Commodity Specialist, USGS and Emily Rowan, ICF International. October and November.
- Cleary, J., N. Roulet and T.R. Moore (2005) "Greenhouse gas emissions from Canadian peat extraction, 1990-2000: A life-cycle analysis." *Ambio* 34:456–461.
- Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2014) *Alaska's Mineral Industry Report (1997–2013)*. Alaska Department of Natural Resources, Fairbanks, AK. Available online at: <<http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=minerals>>.
- IPCC (2013) *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.)]. Published: IPCC, Switzerland.
- IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report (AR4) of the IPCC*. The Intergovernmental Panel on Climate Change, [R.K. Pachauri, A. Reisinger (eds.)]. Geneva, Switzerland.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- Szumigala, D.J. (2011) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. January 18, 2011.
- Szumigala, D.J. (2008) Phone conversation. Dr. David Szumigala, Division of Geological and Geophysical Surveys, Alaska Department of Natural Resources and Emily Rowan, ICF International. October 17, 2008.
- USGS (1991–2015a) *Minerals Yearbook: Peat (1994–2014)*. United States Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb>>.

United States Geological Survey (USGS) (2015b) *Mineral Commodity Summaries: Peat (2014)*. United States Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf>>.

USGS (2015c) *Mineral Commodity Summaries: Peat (2014)*. United States Geological Survey, Reston, VA. Available online at: <<http://minerals.usgs.gov/minerals/pubs/mcs/2015/mcs2015.pdf>>.

Settlements Remaining Settlements: Changes in Carbon Stocks in Urban Trees

deVries, R.E. (1987) A Preliminary Investigation of the Growth and Longevity of Trees in Central Park. M.S. thesis, Rutgers University, New Brunswick, NJ.

Dwyer, J.F., D.J. Nowak, M.H. Noble, and S.M. Sisinni (2000) Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests. General Technical Report PNW-GTR-490, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Fleming, L.E. (1988) Growth Estimation of Street Trees in Central New Jersey. M.S. thesis, Rutgers University, New Brunswick, NJ.

Frelich, L.E. (1992) Predicting Dimensional Relationships for Twin Cities Shade Trees. University of Minnesota, Department of Forest Resources, St. Paul, MN, p. 33.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Nowak, D.J. (2011) Phone conference regarding Changes in Carbon Stocks in Urban Trees estimation methodology. David Nowak, USDA, Jennifer Jenkins, EPA, and Mark Flugge and Nikhil Nadkarni, ICF International. January 4, 2011.

Nowak, D.J. (2009) E-mail correspondence regarding new data for Chicago's urban forest. David Nowak, USDA Forest Service to Nikhil Nadkarni, ICF International. October 7, 2009.

Nowak, D.J. (2007a) "New York City's Urban Forest." USDA Forest Service. Newtown Square, PA, February 2007.

Nowak, D.J. (2007b) E-mail correspondence regarding revised sequestration values and standard errors for sequestration values. David Nowak, USDA Forest Service to Susan Asam, ICF International. October 31, 2007.

Nowak, D.J. (1994) "Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest." In: Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. [E.G. McPherson, D.J. Nowak, and R.A. Rowntree (eds.)]. General Technical Report NE-186. U.S. Department of Agriculture Forest Service, Radnor, PA. pp. 83–94.

Nowak, D.J. (1986) "Silvics of an Urban Tree Species: Norway Maple (*Acer platanoides* L.)." M.S. thesis, College of Environmental Science and Forestry, State University of New York, Syracuse, NY.

Nowak, D.J., Buckelew-Cumming, A., Twardus, D., Hoehn, R., and Mielke, M. (2007) National Forest Health Monitoring Program, Monitoring Urban Forests in Indiana: Pilot Study 2002, Part 2: Statewide Estimates Using the UFORE Model. Northeastern Area Report. NA-FR-01e07, p. 13.

Nowak, D.J. and D.E. Crane (2002) "Carbon Storage and Sequestration by Urban Trees in the United States." *Environmental Pollution* 116(3):381–389.

Nowak, D.J., D.E. Crane, J.C. Stevens, and M. Ibarra (2002) Brooklyn's Urban Forest. General Technical Report NE-290. U.S. Department of Agriculture Forest Service, Newtown Square, PA.

Nowak, D.J., and E.J. Greenfield (2012) Tree and impervious cover in the United States. *Journal of Landscape and Urban Planning* (107) pp. 21-30.

Nowak, D.J., E.J. Greenfield, R.E. Hoehn, and E. Lapoint (2013) Carbon Storage and Sequestration by Trees in Urban and Community Areas of the United States. *Environmental Pollution* 178: 229–236. March 12, 2013.

Nowak, D.J., J.T. Walton, L.G. Kaya, and J.F. Dwyer (2005) "The Increasing Influence of Urban Environments on U.S. Forest Management." *Journal of Forestry* 103(8):377–382.

Smith, W.B. and S.R. Shifley (1984) Diameter Growth, Survival, and Volume Estimates for Trees in Indiana and Illinois. Research Paper NC-257. North Central Forest Experiment Station, U.S. Department of Agriculture Forest Service, St. Paul, MN.

U.S. Census Bureau (2012) "A national 2010 urban area file containing a list of all urbanized areas and urban clusters (including Puerto Rico and the Island Areas) sorted by UACE code." U.S. Census Bureau, Geography Division.

Settlements Remaining Settlements: N₂O Fluxes from Soils

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Ruddy B.C., D.L. Lorenz, and D.K. Mueller (2006) *County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001*. Scientific Investigations Report 2006-5012. U.S. Department of the Interior.

Other: Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

Barlaz, M.A. (2008) "Re: Corrections to Previously Published Carbon Storage Factors." Memorandum to Randall Freed, ICF International. February 28, 2008.

Barlaz, M.A. (2005) "Decomposition of Leaves in Simulated Landfill." Letter report to Randall Freed, ICF Consulting. June 29, 2005.

Barlaz, M.A. (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

De la Cruz, F.B. and M.A. Barlaz (2010) "Estimation of Waste Component Specific Landfill Decay Rates Using Laboratory-Scale Decomposition Data" *Environmental Science & Technology* 44:4722– 4728.

Eleazer, W.E., W.S. Odle, Y. Wang, and M.A. Barlaz (1997) "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Environmental Science & Technology* 31:911–917.

EPA (2015a) *Advancing Sustainable Materials Management: Facts and Figures 2013*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at: <<http://www.epa.gov/osw/nonhaz/municipal/msw99.htm>>.

EPA (2015b) *Advancing Sustainable Materials Management: 2013 Historical (summary) Data Tables*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. Available online at: <http://www.epa.gov/solidwaste/conserve/tools/recmeas/msw_improv.htm#H>.

EPA (1995) *Compilation of Air Pollutant Emission Factors*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. AP-42 Fifth Edition. Available online at: <<http://www3.epa.gov/ttnchie1/ap42/>>.

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. The Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, J. Penman et al. (eds.). Available online at: <<http://www.ipcc-nrgip.iges.or.jp/public/gpglulucf/gpglulucf.htm>>.

Oshins, C. and D. Block (2000) "Feedstock Composition at Composting Sites." *Biocycle* 41(9):31–34.

Tchobanoglou, G., H. Theisen, and S.A. Vigil (1993) *Integrated Solid Waste Management, 1st edition*. McGraw-Hill, NY. Cited by Barlaz (1998) "Carbon Storage during Biodegradation of Municipal Solid Waste Components in Laboratory-Scale Landfills." *Global Biogeochemical Cycles* 12:373–380.

Waste

Landfills

40 CFR Part 60, Subpart CC (2005) Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills, 60.30c--60.36c, Code of Federal Regulations, Title 40. Available online at: <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

40 CFR Part 60, Subpart WWW (2005) Standards of Performance for Municipal Solid Waste Landfills, 60.750--60.759, Code of Federal Regulations, Title 40. Available online at: <http://www.access.gpo.gov/nara/cfr/waisidx_05/40cfr60_05.html>.

BioCycle (2010) "The State of Garbage in America" By L. Arsova, R. Van Haaren, N. Goldstein, S. Kaufman, and N. Themelis. *BioCycle*. December 2010. Available online at: <http://www.jgpress.com/archives/_free/002191.html>.

Bronstein, K., Coburn, J., and R. Schmeltz (2012) "Understanding the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks and Mandatory GHG Reporting Program for Landfills: Methodologies, Uncertainties, Improvements and Deferrals." Prepared for the U.S. EPA International Emissions Inventory Conference, August 2012, Tampa, Florida. Available online at: <<http://www.epa.gov/ttnchie1/conference/ei20/session3/kbronstein.pdf>>.

Czepliel, P., B. Mosher, P. Crill, and R. Harriss (1996) "Quantifying the Effect of Oxidation on Landfill Methane Emissions." *Journal of Geophysical Research*, 101(D11):16721-16730.

EIA (2007) Voluntary Greenhouse Gas Reports for EIA Form 1605B (Reporting Year 2006). Available online at: <<ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/>>.

EPA (2015a) *Landfill Gas-to-Energy Project Database*. Landfill Methane and Outreach Program. August 2015.

EPA (2015b) Greenhouse Gas Reporting Program (GHGRP). 2015 Envirofacts. Subpart HH: Municipal Solid Waste Landfills. Available online at: <<http://www.epa.gov/enviro/facts/ghg/search.html>>.

EPA (2015c) Advancing Sustainable Materials Management: Facts and Figures 2013. June 2015. Available online at: <http://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf>.

EPA (2008) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Draft Section 2.4 Municipal Solid Waste Landfills. October 2008.

EPA (1998) *Compilation of Air Pollution Emission Factors, Publication AP-42*, Section 2.4 Municipal Solid Waste Landfills. November 1998.

EPA (1993) *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress*, U.S. Environmental Protection Agency, Office of Air and Radiation. Washington, D.C. EPA/430-R-93-003. April 1993.

EPA (1988) *National Survey of Solid Waste (Municipal) Landfill Facilities*, U.S. Environmental Protection Agency. Washington, D.C. EPA/530-SW-88-011. September 1988.

ERG (2014) Draft Production Data Supplied by ERG for 1990-2013 for Pulp and Paper, Fruits and Vegetables, and Meat. August.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Mancinelli, R. and C. McKay (1985) "Methane-Oxidizing Bacteria in Sanitary Landfills." *Proc. First Symposium on Biotechnical Advances in Processing Municipal Wastes for Fuels and Chemicals*, Minneapolis, MN, 437-450. August.

Peer, R., S. Thorneloe, and D. Epperson (1993) "A Comparison of Methods for Estimating Global Methane Emissions from Landfills." *Chemosphere*, 26(1-4):387-400.

RTI (2015a) Update the flare correction factor for the 1990-2014 Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA). November 25, 2015.

RTI (2015b) Investigate the potential to update DOC and k values for the Pulp and Paper industry in the US Solid Waste Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA), December 4, 2015. RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA). January 14, 2011.

RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA). January 14, 2011.

RTI (2004) Documentation for Changes to the Methodology for the Inventory of Methane Emissions from Landfills. Memorandum prepared by M. Branscome and J. Coburn (RTI) to E. Scheehle (EPA). August 26, 2004.

Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States – A National Survey. Master of Science thesis submitted to the Department of Earth and Environmental Engineering Fu Foundation School of Engineering and Applied Science, Columbia University. January 3, 2014. Available online at: <http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf>.

Solid Waste Association of North America (SWANA) (1998) *Comparison of Models for Predicting Landfill Methane Recovery*. Publication No. GR-LG 0075. March 1998.

U.S. Census Bureau (2015) Annual Population Estimates, Vintage 2014 April 1, 2010 to July 1, 2014. Available online at: <<http://www.census.gov/popest/data/national/asrh/2014/>>.

Waste Business Journal (WBJ) (2010) Directory of Waste Processing & Disposal Sites 2010.

Wastewater Treatment

Ahn et al. (2010) N₂O Emissions from Activated Sludge Processes, 2008-2009: Results of a National Monitoring Survey in the United States. *Environ. Sci. Technol.* 44: 4505-4511.

Beecher et al. (2007) "A National Biosolids Regulation, Quality, End Use & Disposal Survey, Preliminary Report." Northeast Biosolids and Residuals Association, April 14, 2007.

Benyahia, F., M. Abdulkarim, A. Embaby, and M. Rao. (2006) Refinery Wastewater Treatment: A true Technological Challenge. Presented at the Seventh Annual U.A.E. University Research Conference.

Bertramsen (2016) Email correspondence. Sherry Bertramsen, U.S. Department of Agriculture, to Kara Edquist, ERG. "USDA QuickStats Data Confirmation." February 19, 2016.

Climate Action Reserve (CAR) (2011) Landfill Project Protocol V4.0, June 2011. Available online at: <<http://www.climateactionreserve.org/how/protocols/us-landfill/>>.

Chandran, K. (2012) Greenhouse Nitrogen Emissions from Wastewater Treatment Operation Phase I: Molecular Level Through Whole Reactor Level Characterization. WERF Report U4R07.

Cooper (2014) Email correspondence. Geoff Cooper, Renewable Fuels Association to Deborah Bartram, ERG. "Wet Mill vs. Dry Mill Ethanol Production." December 17, 2014.

DOE (2013) U.S. Department of Energy Bioenergy Technologies Office. Biofuels Basics. Available online at: <http://www1.eere.energy.gov/bioenergy/biofuels_basics.html#Ethanol>. Accessed September 2013.

Donovan (1996) Siting an Ethanol Plant in the Northeast. C.T. Donovan Associates, Inc. Report presented to Northeast Regional Biomass Program (NRBP). (April). Available online at: <<http://www.nrbp.org/pdfs/pub09.pdf>>. Accessed October 2006.

EIA (2016) Energy Information Administration. U.S. Refinery and Blender Net Production of Crude Oil and Petroleum Products (Thousand Barrels). Available online at: <<http://tonto.eia.doe.gov/dnav/pet/hist/mttrpus1a.htm>>. Accessed February 2016.

EPA (2015) U.S. Environmental Protection Agency. *Discharge Monitoring Report (DMR) Pollutant Loading Tool: Data Scope and Limitations*. Available online at: <<http://cfpub.epa.gov/dmr/about-the-data.cfm#scope>>.

EPA (2008) US Environmental Protection Agency. Municipal Nutrient Removal Technologies Reference Document: Volume 2 – Appendices. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C.

EPA (2004) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2004 – Report to Congress. U.S. Environmental Protection Agency, Office of Wastewater Management. Washington, D.C.

EPA (2002) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Industry Point Source Category (40 CFR 432). EPA-821-B-01-007. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. January 2002.

EPA (2000) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 2000 - Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <<http://www.epa.gov/owm/mtb/cwns/2000rtc/toc.htm>>. Accessed July 2007.

EPA (1999) U.S. Environmental Protection Agency. Biosolids Generation, Use and Disposal in the United States. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Washington, D.C. EPA530-R-99-009. September 1999.

EPA (1998) U.S. Environmental Protection Agency. “AP-42 Compilation of Air Pollutant Emission Factors.” Chapter 2.4, Table 2.4-3, page 2.4-13. Available online at: <<http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf>>.

EPA (1997a) U.S. Environmental Protection Agency. Estimates of Global Greenhouse Gas Emissions from Industrial and Domestic Wastewater Treatment. EPA-600/R-97-091. Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency. Washington, D.C. September 1997.

EPA (1997b) U.S. Environmental Protection Agency. Supplemental Technical Development Document for Effluent Guidelines and Standards (Subparts B & E). EPA-821-R-97-011. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1997.

EPA (1996) U.S. Environmental Protection Agency. 1996 Clean Water Needs Survey Report to Congress. Assessment of Needs for Publicly Owned Wastewater Treatment Facilities, Correction of Combined Sewer Overflows, and Management of Storm Water and Nonpoint Source Pollution in the United States. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C. Available online at: <<http://www.epa.gov/owm/mtb/cwns/1996rtc/toc.htm>>. Accessed July 2007.

EPA (1993) U.S. Environmental Protection Agency. Development Document for the Proposed Effluent Limitations Guidelines and Standards for the Pulp, Paper and Paperboard Point Source Category. EPA-821-R-93-019. Office of Water, U.S. Environmental Protection Agency. Washington, D.C. October 1993.

EPA (1992) U.S. Environmental Protection Agency. Clean Watersheds Needs Survey 1992 – Report to Congress. Office of Wastewater Management, U.S. Environmental Protection Agency. Washington, D.C.

EPA (1975) U.S. Environmental Protection Agency. Development Document for Interim Final and Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Fruits, Vegetables, and Specialties Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. United States Environmental Protection Agency, Office of Water. EPA-440/1-75-046. Washington D.C. October 1975.

EPA (1974) U.S. Environmental Protection Agency. Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Apple, Citrus, and Potato Processing Segment of the Canned and Preserved Fruits and Vegetables Point Source Category. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-440/1-74-027-a. March 1974.

ERG (2015). Memorandum: Review of Nitrogen Data Available for Domestic Wastewater N₂O Emissions. Prepared for Rachel Schmetz, EPA. 25 June 2015.

ERG (2014a) Recommended Improvements to the 1990-2013 Wastewater Greenhouse Gas Inventory. September 2014.

ERG (2014b) Recommended Improvements to the 1990-2013 Wastewater Greenhouse Gas Inventory Using the GHGRP Data. September 2014.

ERG (2013a) Revisions to Pulp and Paper Wastewater Inventory. October 2013.

ERG (2013b) Revisions to the Petroleum Wastewater Inventory. October 2013.

ERG (2011) Review of Current Research on Nitrous Oxide Emissions from Wastewater Treatment. April 2011.

ERG (2008) Planned Revisions of the Industrial Wastewater Inventory Emission Estimates for the 1990-2007 Inventory. August 10, 2008.

ERG (2006) Memorandum: Assessment of Greenhouse Gas Emissions from Wastewater Treatment of U.S. Ethanol Production Wastewaters. Prepared for Melissa Weitz, EPA. 10 October 2006.

FAO (2016) FAOSTAT-Forestry Database. Available online at: <<http://faostat3.fao.org/home/index.html#DOWNLOAD>>. Accessed February 2016.

Global Water Research Coalition (GWRC) (2011) N₂O and CH₄ Emission from Wastewater Collection and Treatment Systems - Technical Report. GWRC Report 2011-30.

Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. (2004) Recommended Standards for Wastewater Facilities (Ten-State Standards).

IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. [Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds.)]. Published: IPCC, Switzerland.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.

Leverenz, H.L., G. Tchobanoglous, and J.L. Darby (2010) "Evaluation of Greenhouse Gas Emissions from Septic Systems". Water Environment Research Foundation. Alexandria, VA.

Lockwood-Post (2002) Lockwood-Post's Directory of Pulp, Paper and Allied Trades, Miller-Freeman Publications. San Francisco, CA.

McFarland (2001) Biosolids Engineering, New York: McGraw-Hill, p. 2.12.

Merrick (1998) Wastewater Treatment Options for the Biomass-to-Ethanol Process. Report presented to National Renewable Energy Laboratory (NREL). Merrick & Company. Subcontract No. AXE-8-18020-01. October 22, 1998.

Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment, Disposal and Reuse, 4th ed. McGraw Hill Publishing.

Nemerow, N.L. and A. Dasgupta (1991) Industrial and Hazardous Waste Treatment. Van Nostrand Reinhold. NY. ISBN 0-442-31934-7.

NRBP (2001) Northeast Regional Biomass Program. An Ethanol Production Guidebook for Northeast States. Washington, D.C. (May 3). Available online at: <<http://www.nrbp.org/pdfs/pub26.pdf>>. Accessed October 2006.

Rendleman, C.M. and Shapouri, H. (2007) New Technologies in Ethanol Production. USDA Agricultural Economic Report Number 842.

RFA (2016) Renewable Fuels Association. Historic U.S. Fuel Ethanol Production. Available online at: <<http://www.ethanolrfa.org/pages/statistics>>. Accessed February 2016.

Ruocco (2006a) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. “Capacity of Bio-Methanators (Dry Milling).” October 6, 2006.

Ruocco (2006b) Email correspondence. Dr. Joe Ruocco, Phoenix Bio-Systems to Sarah Holman, ERG. “Capacity of Bio-Methanators (Wet Milling).” October 16, 2006.

Scheehle, E.A., and Doorn, M.R. (2001) “Improvements to the U.S. Wastewater Methane and Nitrous Oxide Emissions Estimate.” July 2001.

Sullivan (SCS Engineers) (2010) The Importance of Landfill Gas Capture and Utilization in the U.S. Presented to SWICS, April 6, 2010. Available online at:
[<http://www.scsengineers.com/Papers/Sullivan_Importance_of_LFG_Capture_and_Utilization_in_the_US.pdf>](http://www.scsengineers.com/Papers/Sullivan_Importance_of_LFG_Capture_and_Utilization_in_the_US.pdf).

Sullivan (SCS Engineers) (2007) Current MSW Industry Position and State of the Practice on Methane Destruction Efficiency in Flares, Turbines, and Engines. Presented to Solid Waste Industry for Climate Solutions (SWICS). July 2007. Available online at:
[<http://www.scsengineers.com/Papers/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf>](http://www.scsengineers.com/Papers/Sullivan_LFG_Destruction_Efficiency_White_Paper.pdf).

UNFCCC (2012) CDM Methodological tool, Project emissions from flaring (Version 02.0.0). EB 68 Report. Annex 15. Available online at: <<http://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-06-v1.pdf>>/history_view>.

U.S. Census Bureau (2016) International Database. Available online at: <<http://www.census.gov/ipc/www/idb/>> and <<http://www.census.gov/ipc/www/idbprint.html>>. Accessed February 2016.

U.S. Census Bureau (2013) “American Housing Survey.” Table 1A-4: Selected Equipment and Plumbing--All Housing Units. From 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, 2011 and 2013 reports. Available online at: <<http://www.census.gov/hhes/www/housing/ahs/nationaldata.html>>. Accessed February 2016.

USDA (2016a) U.S. Department of Agriculture. National Agricultural Statistics Service. Washington, D.C. Available online at: <http://www.nass.usda.gov/Publications/Ag_Statistics/index.asp> and <http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/>. Accessed February 2016.

USDA (2016b) U.S. Department of Agriculture. Economic Research Service. Nutrient Availability. Washington D.C. Available online at:
<http://www.ers.usda.gov/datafiles/Food_Availability_Per_Capita_Data_System/Nutrient_Availability/nutrients.xls>. Accessed February 2016.

USPoultry (2006) Email correspondence. John Starkey, USPOULTRY to D. Bartram, ERG. 30 August 2006.

White and Johnson (2003) White, P.J. and Johnson, L.A. Editors. Corn: Chemistry and Technology. 2nd ed. AACC Monograph Series. American Association of Cereal Chemists. St. Paul, MN.

Willis et al. (2013) Methane Evolution from Lagoons and Ponds. Prepared for the Water Environment Research Foundation under contract U2R08c.

World Bank (1999) Pollution Prevention and Abatement Handbook 1998, Toward Cleaner Production. The International Bank for Reconstruction and Development, The World Bank, Washington, D.C. ISBN 0-8213-3638-X.

Composting

BioCycle (2010) *The State of Garbage in America*. Prepared by Rob van Haaren, Nickolas Themelis and Nora Goldstein. Available online at: <http://www.biocycle.net/images/art/1010/bc101016_s.pdf>.

EPA (2015) *Advancing Sustainable Materials Management: Facts and Figures 2013*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at:
<http://www.epa.gov/wastes/nonhaz/municipal/pubs/2013_advncng_smm_rpt.pdf>.

EPA (2014) *Municipal Solid Waste in the United States: 2012 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at:
<http://epa.gov/epawaste/nonhaz/municipal/pubs/2012_msw_dat_tbls.pdf>.

- EPA (2011) *Municipal Solid Waste in the United States: 2010 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf>.
- EPA (2007) *Municipal Solid Waste in the United States: 2006 Facts and Figures*. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. Available online at: <<http://www.epa.gov/osw/nonhaz/municipal/pubs/06data.pdf>>.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 5: Waste, Chapter 4: Biological Treatment of Solid Waste, Table 4.1. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan. Available online at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf>.
- Shin, D. (2014) Generation and Disposition of Municipal Solid Waste (MSW) in the United States – A National Survey. Table 3. Master of Science thesis, Department of Earth and Environmental Engineering, Fu Foundation School of Engineering and Applied Science, Columbia University. Available online at: <http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf>.
- U.S. Census Bureau (2015) Population Estimates: Vintage 2014 Annual Estimates Available online at: <<http://www.census.gov/popest/data/national/totals/2014/index.html>>.
- U.S. Composting Council (2010) *Yard Trimmins Bans: Impact and Support*. Prepared by Stuart Buckner, Executive Director, U.S. Composting Council. Available online at: <<http://recyclingorganizations.org/webinars/RONA-YT-Ban-impacts-and-support-8.19.pdf>>.

Waste Sources of Indirect Greenhouse Gas Emissions

- EPA (2015) “1970 - 2014 Average annual emissions, all criteria pollutants in MS Excel.” National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards, March 2015. Available online at: <<http://www.epa.gov/ttn/chief/trends/index.html>>.
- EPA (2003) E-mail correspondence containing preliminary ambient air pollutant data. Office of Air Pollution and the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. December 22, 2003.
- EPA (1997) *Compilation of Air Pollutant Emission Factors, AP-42*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. Research Triangle Park, NC. October 1997.

Recalculations and Improvements

- Domke, G.M., Perry, C.H., Walters, B.F., Nave, L.E., Woodall, C.W., Swanston, C.W. (In Preparation) Towards field-based estimates of soil organic carbon in forests of the United States.
- EPA (2015) Rule and Implementation Information for Standards of Performance for Municipal Solid Waste Landfills, Docket #A-88-09. Available at <<http://www3.epa.gov/ttn/atw/landfill/landflpg.html>>.
- IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. [H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Hayama, Kanagawa, Japan.
- RTI (2015) Investigate the potential to update DOC and k values for the Pulp and Paper industry in the US Solid Waste Inventory. Memorandum prepared by K. Bronstein and M. McGrath for R. Schmeltz (EPA), December 4, 2015. RTI (2011) Updated Research on Methane Oxidation in Landfills. Memorandum prepared by K. Weitz (RTI) for R. Schmeltz (EPA), January 14, 2011.
- Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Anderson, H.-E., Clough, B.J., Cohen, W.B., Griffith, D.M., Hagan, S.C., Hanou, I.S.; Nichols, M.C., Perry, C.H., Russell, M.B., Westfall, J.A., Wilson, B.T. (2015) The US Forest Carbon Accounting Framework: Stocks and Stock change 1990-2016.

Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 pp.