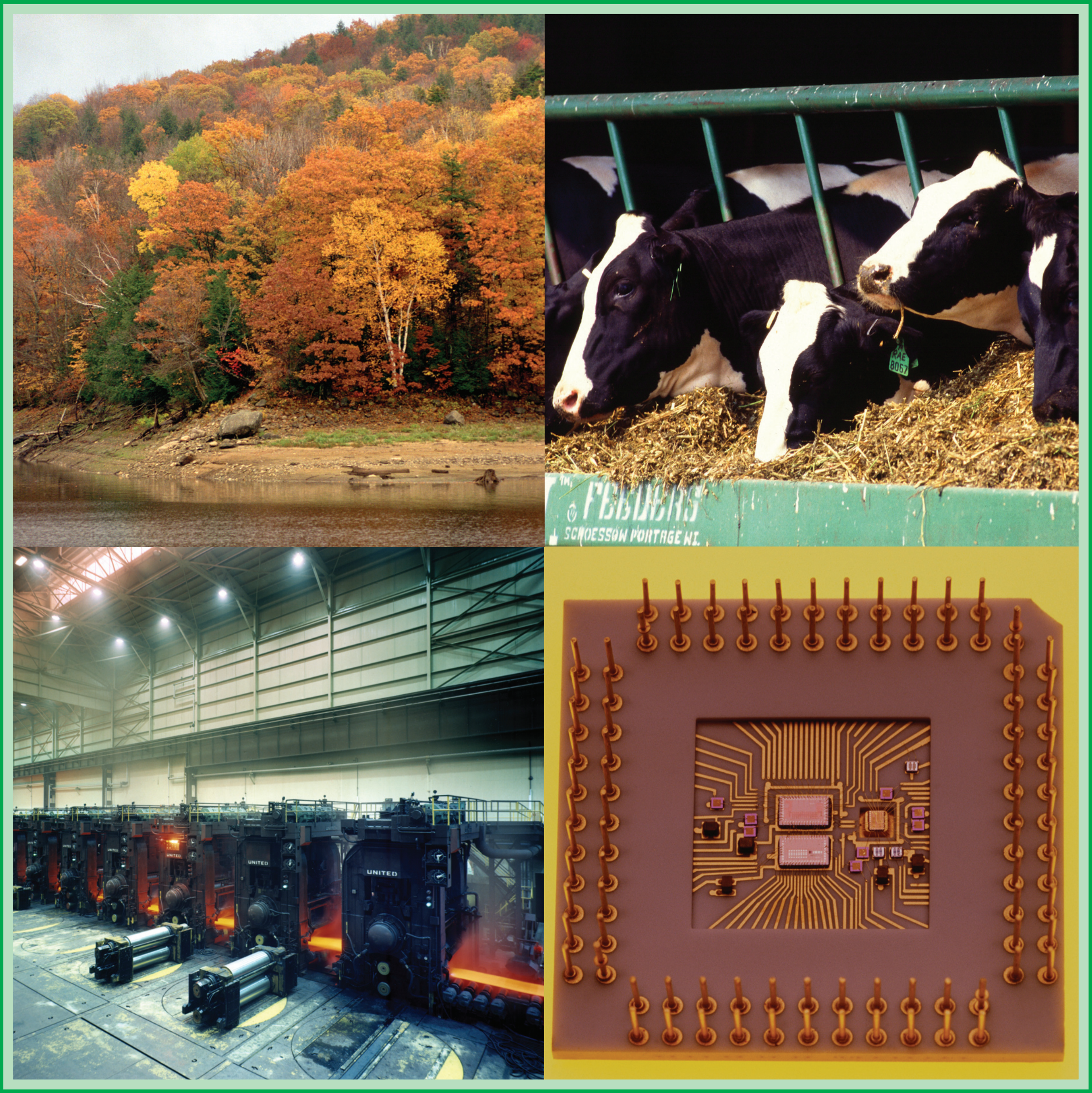
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2007



INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS:

1990–2007

April 15, 2009

U.S. Environmental Protection Agency

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U.S.A.

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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).[1] 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.[2] 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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[1] See Article 4(1)(a) of the United Nations Framework Convention on Climate Change <http://www.unfccc.int>.

[2] See <http://www.epa.gov/globalwarming/publications/emissions>.

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Executive Summary

An emissions inventory that identifies and quantifies a country's primary anthropogenic[1] sources and sinks of greenhouse gases is essential for addressing climate change. This inventory adheres to both (1) a comprehensive and detailed set of methodologies for estimating 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 2007. 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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000), and the IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003). Additionally, the U.S. emissions inventory has begun to incorporate new methodologies and data from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The structure of this report is consistent with the UNFCCC guidelines for inventory reporting.[4] For most source categories, the Intergovernmental Panel on Climate Change (IPCC) methodologies were expanded, resulting in a more comprehensive and detailed estimate of emissions.

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[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC/UNEP/OECD/IEA 1997).

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

[3] Article 4(1)(a) of the UNFCCC (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/cop8/08.pdf>.

Box ES-1: 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 IPCC *Good Practice Guidance* (IPCC 2000), which states, regarding recalculations of the time series, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected." 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 2006) has been recalculated to reflect the change, per IPCC *Good Practice Guidance*. 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.

ES.1. Background Information

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in their national greenhouse gas emission inventories.[5] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—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 emission inventories.

There are also several gases that do not have a direct global warming effect but indirectly affect terrestrial and/or solar radiation absorption by influencing the formation or destruction of greenhouse gases, including tropospheric and stratospheric ozone. These gases include carbon monoxide (CO), oxides of nitrogen (NO_x), and non-CH_4 volatile organic compounds (NMVOCs). Aerosols, which are extremely small particles or liquid droplets, such as those produced by sulfur dioxide (SO_2) or elemental carbon emissions, can also affect the absorptive characteristics of the atmosphere.

Although the direct greenhouse gases CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric concentrations. From the pre-industrial era (i.e., ending about 1750) to 2005, concentrations of these greenhouse gases have increased globally by 36, 148, and 18 percent, respectively (IPCC 2007).

Beginning in the 1950s, the use of CFCs and other stratospheric ozone depleting substances (ODS) increased by nearly 10 percent per year until the mid-1980s, when international concern about ozone depletion led to the entry into force of the *Montreal Protocol*. Since then, the production of ODS is being phased out. In recent years, use of ODS substitutes such as HFCs and PFCs has grown as they begin to be phased in as replacements for CFCs and HCFCs. Accordingly, atmospheric concentrations of these substitutes have been growing (IPCC 2007).

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[5] Emission estimates of CFCs, HCFCs, halons and other ozone depleting substances are included in the annexes of this Inventory for informational purposes.

Global Warming Potentials

Gases in the atmosphere can contribute to the greenhouse effect 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).[6] 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 2001). Direct radiative effects occur when the gas itself is a greenhouse gas. The reference gas used is CO_2, and therefore GWP-weighted emissions are measured in teragrams (or million metric tons) of CO_2 equivalents (Tg CO_2 Eq.).[7,8] All gases in this Executive Summary are presented in units of Tg CO_2 Eq.

The UNFCCC reporting guidelines for national inventories were updated in 2006,[9] but continue to require the use of GWPs from the IPCC Second Assessment Report (SAR) (IPCC 1996). This requirement ensures that current estimates of aggregate greenhouse gas emissions for 1990 to 2007 are consistent with estimates developed prior to the publication of the IPCC Third Assessment Report (TAR) and the IPCC Fourth Assessment Report (AR4). Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission values using the SAR GWPs versus the TAR and AR4 GWPs 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 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*	21
N_2O	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

Source: IPCC (1996)

* The CH_4 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 the production of CO_2 is not included.

Global warming potentials are not provided for CO, NO_x, NMVOCs, SO_2, and aerosols because there is no agreed-upon method to estimate the contribution of gases that are short-lived in the atmosphere, spatially variable, or have only indirect effects on radiative forcing (IPCC 1996).

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

In 2007, total U.S. greenhouse gas emissions were 7,150.1 Tg CO_2 Eq. Overall, total U.S. emissions have risen by 17 percent from 1990 to 2007. Emissions rose from 2006 to 2007, increasing by 1.4 percent (99.0 Tg CO_2 Eq.). The following factors were primary contributors to this increase: (1) cooler winter and warmer summer conditions in 2007 than in 2006 increased the demand for heating fuels and contributed to the increase in the demand for electricity, (2) increased consumption of fossil fuels to generate electricity and (3) a significant decrease (14.2 percent) in hydropower generation used to meet this demand.

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[6] 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.

[7] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

[8] One teragram is equal to 10^{12} grams (g) or one million metric tons.

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

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. Table ES-2 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2007.

Figure ES-4 illustrates the relative contribution of the direct greenhouse gases to total U.S. emissions in 2007. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing approximately 85.4 percent of total greenhouse gas emissions. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion. CH_4 emissions, which have declined from 1990 levels, resulted primarily from enteric fermentation associated with domestic livestock, decomposition of wastes in landfills, and natural gas systems. Agricultural soil management and mobile source fuel combustion were the major sources of N_2O emissions. The emissions of substitutes for ozone depleting substances and emissions of HFC-23 during the production of HCFC-22 were the primary contributors to aggregate HFC emissions. Electrical transmission and distribution systems accounted for most SF_6 emissions, while PFC emissions resulted as a by-product of primary aluminum production and from semiconductor manufacturing.

Overall, from 1990 to 2007, total emissions of CO_2 increased by 1,026.7 Tg CO_2 Eq. (20.2 percent), while CH_4 and N_2O emissions decreased by 31.2 Tg CO_2 Eq. (5.1 percent) and 3.1 Tg CO_2 Eq. (1.0 percent), respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 59.0 Tg CO_2 Eq. (65.2 percent). From 1990 to 2007, HFCs increased by 88.6 Tg CO_2 Eq. (240.0 percent), PFCs decreased by 13.3 Tg CO_2 Eq. (64.0 percent), and SF_6 decreased by 16.3 Tg CO_2 Eq. (49.8 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon sequestration in forests, trees in urban areas, agricultural soils, and landfilled yard trimmings and food scraps, which, in aggregate, offset 14.9 percent of total emissions in 2007. The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

Figure ES-1

U.S. Greenhouse Gas Emissions by Gas

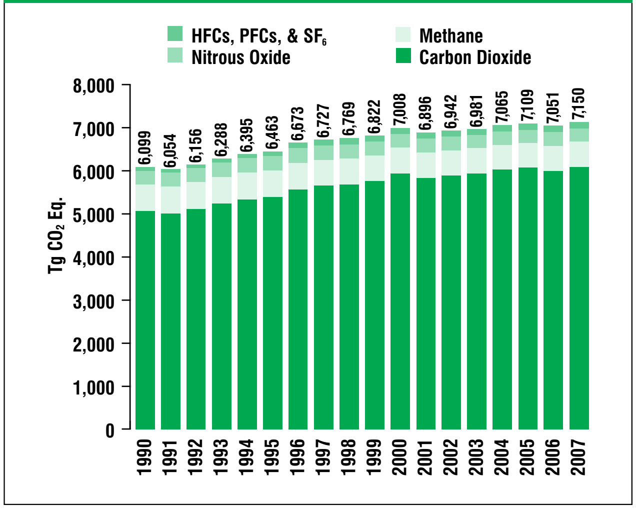


Figure ES-2

Annual Percent Change in U.S. Greenhouse Gas Emissions

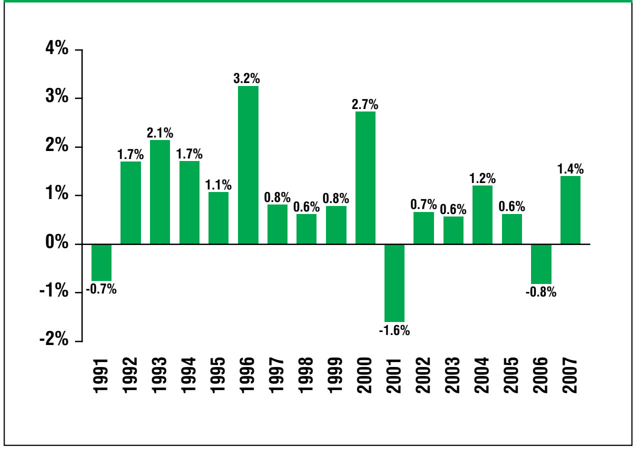


Figure ES-3

Cumulative Change in U.S. Greenhouse Gas Emissions Relative to 1990

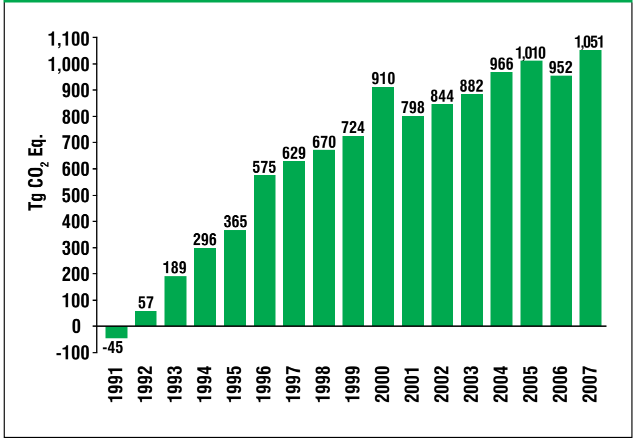


Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**5,076.7**	**5,407.9**	**5,955.2**	**6,090.8**	**6,014.9**	**6,103.4**
Fossil Fuel Combustion	4,708.9	5,013.9	5,561.5	5,723.5	5,635.4	5,735.8
Electricity Generation	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
Transportation	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Industrial	834.2	862.6	844.6	828.0	844.5	845.4
Residential	337.7	354.4	370.4	358.0	321.9	340.6
Commercial	214.5	224.4	226.9	221.8	206.0	214.4
U.S. Territories	28.3	35.0	36.2	53.2	54.8	50.8
Non-Energy Use of Fuels	117.0	137.5	144.5	138.1	145.1	133.9
Iron and Steel Production & Metallurgical Coke Production	109.8	103.1	95.1	73.2	76.1	77.4
Cement Production	33.3	36.8	41.2	45.9	46.6	44.5
Natural Gas Systems	33.7	33.8	29.4	29.5	29.5	28.7
Incineration of Waste	10.9	15.7	17.5	19.5	19.8	20.8
Lime Production	11.5	13.3	14.1	14.4	15.1	14.6
Ammonia Production and Urea Consumption	16.8	17.8	16.4	12.8	12.3	13.8
Cropland Remaining Cropland	7.1	7.0	7.5	7.9	7.9	8.0
Limestone and Dolomite Use	5.1	6.7	5.1	6.8	8.0	6.2
Aluminum Production	6.8	5.7	6.1	4.1	3.8	4.3
Soda Ash Production and Consumption	4.1	4.3	4.2	4.2	4.2	4.1
Petrochemical Production	2.2	2.8	3.0	2.8	2.6	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.8	1.9	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	1.3	1.7	1.9
Ferroalloy Production	2.2	2.0	1.9	1.4	1.5	1.6
Phosphoric Acid Production	1.5	1.5	1.4	1.4	1.2	1.2
Wetlands Remaining Wetlands	1.0	1.0	1.2	1.1	0.9	1.0
Zinc Production	0.9	1.0	1.1	0.5	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(841.4)*	*(851.0)*	*(717.5)*	*(1,122.7)*	*(1,050.5)*	*(1,062.6)*
Biomass—Wood	*215.2*	*229.1*	*218.1*	*208.9*	*209.9*	*209.8*
International Bunker Fuels[b]	*114.3*	*101.6*	*99.0*	*111.5*	*110.5*	*108.8*
Biomass—Ethanol[b]	*4.2*	*7.7*	*9.2*	*22.6*	*30.5*	*38.0*
CH_4	**616.6**	**615.8**	**591.1**	**561.7**	**582.0**	**585.3**
Enteric Fermentation	133.2	143.6	134.4	136.0	138.2	139.0
Landfills	149.2	144.3	122.3	127.8	130.4	132.9
Natural Gas Systems	129.6	132.6	130.8	106.3	104.8	104.7
Coal Mining	84.1	67.1	60.5	57.1	58.4	57.6
Manure Management	30.4	34.5	37.9	41.8	41.9	44.0
Forest Land Remaining Forest Land	4.6	6.1	20.6	14.2	31.3	29.0
Petroleum Systems	33.9	32.0	30.3	28.3	28.3	28.8
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4
Stationary Combustion	7.4	7.1	6.6	6.7	6.3	6.6
Rice Cultivation	7.1	7.6	7.5	6.8	5.9	6.2
Abandoned Underground Coal Mines	6.0	8.2	7.4	5.6	5.5	5.7
Mobile Combustion	4.7	4.3	3.4	2.5	2.4	2.3

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

Gas/Source	1990	1995	2000	2005	2006	2007
Composting	0.3	0.7	1.3	1.6	1.6	1.7
Petrochemical Production	0.9	1.1	1.2	1.1	1.0	1.0
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.9	0.8	0.9
Iron and Steel Production & Metallurgical Coke Production	1.0	1.0	0.9	0.7	0.7	0.7
Ferroalloy Production	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**315.0**	**334.1**	**329.2**	**315.9**	**312.1**	**311.9**
Agricultural Soil Management	200.3	202.3	204.5	210.6	208.4	207.9
Mobile Combustion	43.7	53.7	52.8	36.7	33.5	30.1
Nitric Acid Production	20.0	22.3	21.9	18.6	18.2	21.7
Manure Management	12.1	12.9	14.0	14.2	14.6	14.7
Stationary Combustion	12.8	13.3	14.5	14.8	14.5	14.7
Adipic Acid Production	15.3	17.3	6.2	5.9	5.9	5.9
Wastewater Treatment	3.7	4.0	4.5	4.8	4.8	4.9
N_2O from Product Uses	4.4	4.6	4.9	4.4	4.4	4.4
Forest Land Remaining Forest Land	0.5	0.8	2.4	1.8	3.5	3.3
Composting	0.4	0.8	1.4	1.7	1.8	1.8
Settlements Remaining Settlements	1.0	1.2	1.2	1.5	1.5	1.6
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.5	0.5
Incineration of Waste	0.5	0.5	0.4	0.4	0.4	0.4
Wetlands Remaining Wetlands	+	+	+	+	+	+
International Bunker Fuels[b]	*1.1*	*0.9*	*0.9*	*1.0*	*1.0*	*1.0*
HFCs	**36.9**	**61.8**	**100.1**	**116.1**	**119.1**	**125.5**
Substitution of Ozone Depleting Substances[c]	0.3	28.5	71.2	100.0	105.0	108.3
HCFC-22 Production	36.4	33.0	28.6	15.8	13.8	17.0
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.3	0.3
PFCs	**20.8**	**15.6**	**13.5**	**6.2**	**6.0**	**7.5**
Aluminum Production	18.5	11.8	8.6	3.0	2.5	3.8
Semiconductor Manufacture	2.2	3.8	4.9	3.2	3.5	3.6
SF_6	**32.8**	**28.1**	**19.2**	**17.9**	**17.0**	**16.5**
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.0
Semiconductor Manufacture	0.5	0.9	1.1	1.0	1.0	0.8
Total	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Parentheses indicate negative values or sequestration. The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total.

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

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

Note: Totals may not sum due to independent rounding.

Figure ES-4

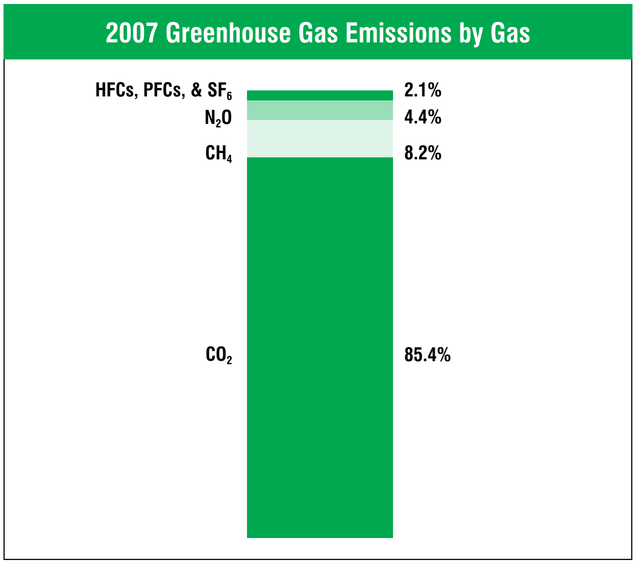
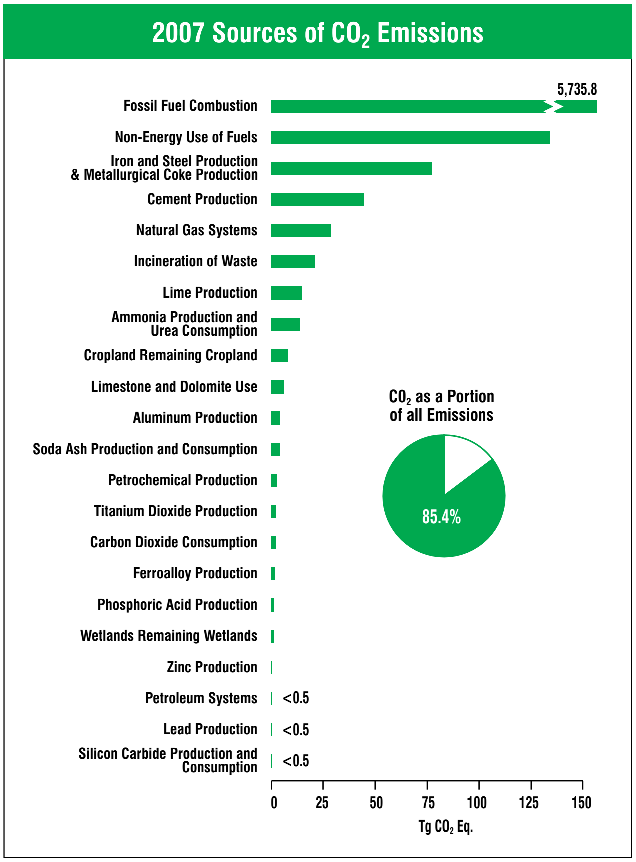

2007 Greenhouse Gas Emissions by Gas

Figure ES-5


2007 Sources of CO$_2$ Emissions

Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO$_2$ are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, carbon fluxes among these various reservoirs are roughly balanced. Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO$_2$ have risen about 36 percent (IPCC 2007), principally due to the combustion of fossil fuels. Within the United States, fuel combustion accounted for 94 percent of CO$_2$ emissions in 2007. Globally, approximately 29,195 Tg of CO$_2$ were added to the atmosphere through the combustion of fossil fuels in 2006, of which the United States accounted for about 20 percent.[10] Changes in land use and forestry practices can also emit CO$_2$ (e.g., through conversion of forest land to agricultural or urban use) or can act as a sink for CO$_2$ (e.g., through net additions to forest biomass).

U.S. anthropogenic sources of CO$_2$ are shown in Figure ES-5. As the largest source of U.S. greenhouse gas emissions, CO$_2$ from fossil fuel combustion has accounted for approximately 79 percent of GWP-weighted emissions since 1990, growing slowly from 77 percent of total GWP-weighted emissions in 1990 to 80 percent in 2007. Emissions of CO$_2$ from fossil fuel combustion increased at an average annual rate of 1.3 percent from 1990 to 2007. The fundamental factors influencing this trend include (1) a generally growing domestic economy over the last 17 years, and (2) significant overall growth in emissions from electricity generation and transportation activities. Between 1990 and 2007, CO$_2$ emissions from fossil fuel combustion increased from 4,708.9 Tg CO$_2$ Eq. to 5,735.8 Tg CO$_2$ Eq.—a 21.8 percent total increase over the eighteen-year period. From 2006 to 2007, these emissions increased by 100.4 Tg CO$_2$ Eq. (1.8 percent).

Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends. Changes in CO$_2$ emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States 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

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[10] Global CO$_2$ emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2006* (EIA 2008b).

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.

The five major fuel consuming sectors contributing to CO_2 emissions from fossil fuel combustion are electricity generation, transportation, industrial, residential, and commercial. CO_2 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 CO_2 emissions from fossil fuel combustion by end-use sector.

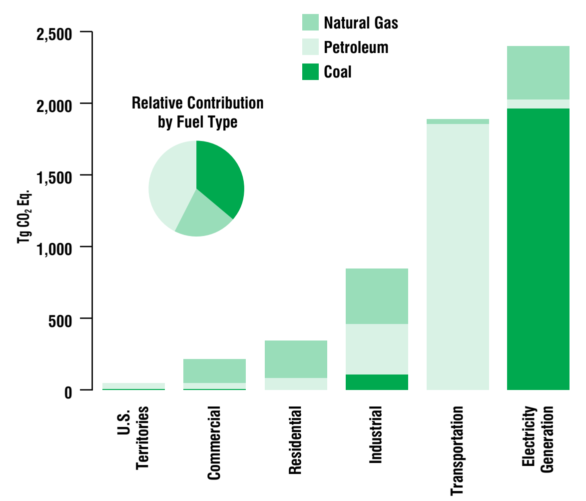
Transportation End-Use Sector. Transportation activities (excluding international bunker fuels) accounted for 33 percent of CO_2 emissions from fossil fuel combustion in 2007.[11] Virtually all of the energy consumed in this end-use sector came from petroleum products. Nearly 60 percent of the emissions resulted from gasoline consumption for personal vehicle use. The remaining emissions came from other transportation activities, including the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircraft.

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is consumed by industry, accounted for 27 percent of CO_2 from fossil fuel combustion in 2007. Just over half 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.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2007. Both sectors relied heavily on electricity for meeting energy demands, with 72 and 79 percent, respectively, of their emissions attributable to electricity consumption for lighting, heating, cooling, and

Figure ES-6

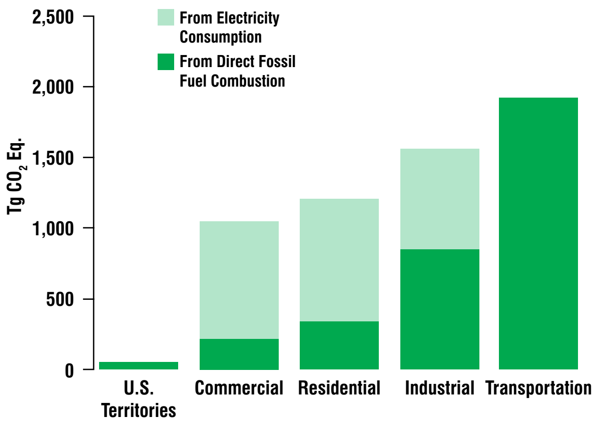
2007 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

Figure ES-7

2007 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



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[11] If emissions from international bunker fuels are included, the transportation end-use sector accounted for 35 percent of U.S. emissions from fossil fuel combustion in 2007.

Table ES-3: CO_2 Emissions from Fossil Fuel Combustion by Fuel Consuming End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2005	2006	2007
Transportation	**1,487.5**	**1,601.7**	**1,803.7**	**1,886.2**	**1,885.4**	**1,892.2**
Combustion	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Electricity	3.0	3.0	3.4	4.7	4.5	4.8
Industrial	**1,516.8**	**1,575.5**	**1,629.6**	**1,558.5**	**1,550.7**	**1,553.4**
Combustion	834.2	862.6	844.6	828.0	844.5	845.4
Electricity	682.6	712.9	785.0	730.5	706.2	708.0
Residential	**927.1**	**993.3**	**1,128.2**	**1,207.2**	**1,145.9**	**1,198.0**
Combustion	337.7	354.4	370.4	358.0	321.9	340.6
Electricity	589.4	638.8	757.9	849.2	824.1	857.4
Commercial	**749.2**	**808.5**	**963.8**	**1,018.4**	**998.6**	**1,041.4**
Combustion	214.5	224.4	226.9	221.8	206.0	214.4
Electricity	534.7	584.1	736.8	796.6	792.5	827.1
U.S. Territories[a]	**28.3**	**35.0**	**36.2**	**53.2**	**54.8**	**50.8**
Total	**4,708.9**	**5,013.9**	**5,561.5**	**5,723.5**	**5,635.4**	**5,735.8**
Electricity Generation	**1,809.7**	**1,938.9**	**2,283.2**	**2,381.0**	**2,327.3**	**2,397.2**

[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.

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

operating appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking.

Electricity Generation. The United States relies on electricity to meet a significant portion of its energy demands, especially for lighting, electric motors, heating, and air conditioning. Electricity generators consumed 36 percent of U.S. energy from fossil fuels and emitted 42 percent of the CO_2 from fossil fuel combustion in 2007. The type of fuel combusted by electricity generators has a significant effect on their emissions. For example, some electricity is generated with low CO_2 emitting energy technologies, particularly non-fossil options such as nuclear, hydroelectric, or geothermal energy. However, electricity generators rely on coal for over half of their total energy requirements and accounted for 94 percent of all coal consumed for energy in the United States in 2007. Consequently, changes in electricity demand have a significant impact on coal consumption and associated CO_2 emissions.

Other significant CO_2 trends included the following:

- CO_2 emissions from non-energy use of fossil fuels have increased 16.9 Tg CO_2 Eq. (14.5 percent) from 1990 to 2007. Emissions from non-energy uses of fossil fuels were 133.9 Tg CO_2 Eq. in 2007, which constituted 2.2 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- CO_2 emissions from iron and steel production and metallurgical coke production increased slightly from 2006 to 2007 (1.3 Tg CO_2 Eq.), but have decreased by 29.5 percent to 77.4 Tg CO_2 Eq. from 1990 to 2007, due to restructuring of the industry, technological improvements, and increased scrap utilization.
- In 2007, CO_2 emissions from cement production decreased slightly by 2.0 Tg CO_2 Eq. (4.4 percent) from 2006 to 2007. This decrease occurs despite the overall increase over the time series. After falling in 1991 by two percent from 1990 levels, cement production emissions grew every year through 2006. Overall, from 1990 to 2007, emissions from cement production increased by 34 percent, an increase of 11.2 Tg CO_2 Eq.
- CO_2 emissions from incineration of waste (20.8 Tg CO_2 Eq. in 2007) increased by 9.8 Tg CO_2 Eq. (90 percent) from 1990 to 2007, as the volume of plastics and other fossil carbon-containing materials in the waste stream grew.
- Net CO_2 sequestration from Land Use, Land-Use Change, and Forestry increased by 221.1 Tg CO_2 Eq. (26 percent) from 1990 to 2007. This increase was primarily due to an increase in the rate of net carbon accumulation

in forest carbon stocks, particularly in aboveground and belowground tree biomass. Annual carbon accumulation in landfilled yard trimmings and food scraps slowed over this period, while the rate of carbon accumulation in urban trees increased.

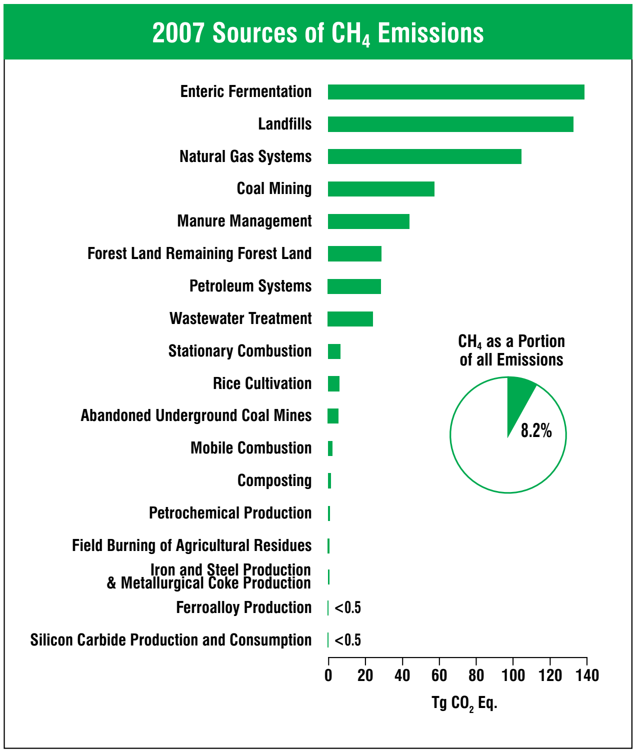
Methane Emissions

According to the IPCC, CH_4 is more than 20 times as effective as CO_2 at trapping heat in the atmosphere. Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 148 percent (IPCC 2007). Anthropogenic sources of CH_4 include landfills, natural gas and petroleum systems, agricultural activities, coal mining, wastewater treatment, stationary and mobile combustion, and certain industrial processes (see Figure ES-8).

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

- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2007, enteric fermentation CH_4 emissions were 139.0 Tg CO_2 Eq. (approximately 24 percent of total CH_4 emissions), which represents an increase of 5.8 Tg CO_2 Eq., or 4.3 percent, since 1990.
- Landfills are the second largest anthropogenic source of CH_4 emissions in the United States, accounting for approximately 23 percent of total CH_4 emissions (132.9 Tg CO_2 Eq.) in 2007. From 1990 to 2007, net CH_4 emissions from landfills decreased by 16.3 Tg CO_2 Eq. (11 percent), with small increases occurring in some interim years, including 2007. This downward trend in overall emissions is the result of increases in the amount of landfill gas collected and combusted,[12] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.
- CH_4 emissions from natural gas systems were 104.7 Tg CO_2 Eq. in 2007; emissions have declined by 24.9 Tg CO_2 Eq. (19 percent) since 1990. This decline has been due to improvements in technology and management practices, as well as some replacement of old equipment.

Figure ES-8



2007 Sources of CH_4 Emissions

- In 2007, CH_4 emissions from coal mining were 57.6 Tg CO_2 Eq., a 0.8 Tg CO_2 Eq. (1.3 percent) decrease over 2006 emission levels. The overall decline of 26.4 Tg CO_2 Eq. (31 percent) from 1990 results from the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- CH_4 emissions from manure management increased by 44.7 percent for CH_4, from 30.4 Tg CO_2 Eq. in 1990 to 44.0 Tg CO_2 Eq. in 2007. 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 CH_4 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.

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[12] The CO_2 produced from combusted landfill CH_4 at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

Nitrous Oxide Emissions

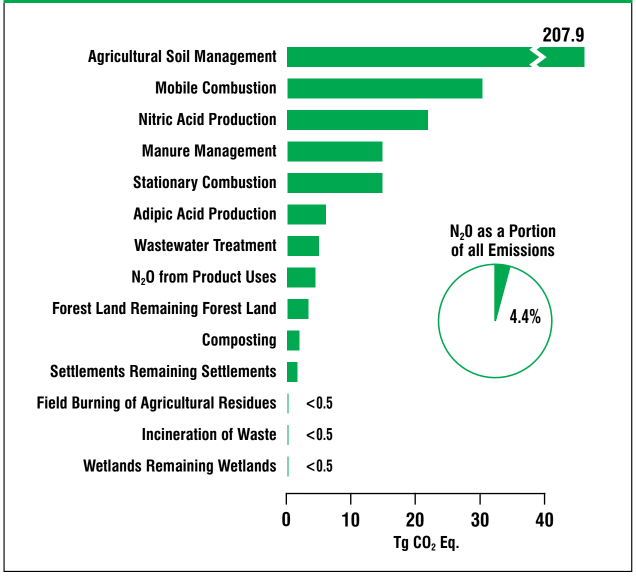
N_2O is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy-related, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is approximately 300 times more powerful than CO_2 at trapping heat in the atmosphere. Since 1750, the global atmospheric concentration of N_2O has risen by approximately 18 percent (IPCC 2007). The main anthropogenic activities producing N_2O in the United States are agricultural soil management, fuel combustion in motor vehicles, nitric acid production, stationary fuel combustion, manure management, and adipic acid production (see Figure ES-9).

Some significant trends in U.S. emissions of N_2O include the following:

- Agricultural soils produced approximately 67 percent of N_2O emissions in the United States in 2007. Estimated emissions from this source in 2007 were 207.9 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2007, although overall emissions were 3.8 percent higher in 2007 than in 1990. N_2O emissions from this source have not shown any significant long-term trend, as they are highly sensitive to the amount of N applied to soils, which has not changed significantly over the time-period, and to weather patterns and crop type.
- In 2007, N_2O emissions from mobile combustion were 30.1 Tg CO_2 Eq. (approximately 10 percent of U.S. N_2O emissions). From 1990 to 2007, N_2O emissions from mobile combustion decreased by 31 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to a steady decline in N_2O from this source.
- N_2O emissions from adipic acid production were 5.9 Tg CO_2 Eq. in 2007, and have decreased significantly since 1996 from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased 61 percent since 1990, and emissions from adipic acid production have fluctuated by less than 1.2 Tg CO_2 Eq. annually since 1998.

Figure ES-9

2007 Sources of N_2O Emissions



HFC, PFC, and SF_6 Emissions

HFCs and PFCs are families of synthetic chemicals that are used as alternatives to the ODSs, which are being phased out under the *Montreal Protocol* and *Clean Air Act Amendments of 1990*. HFCs and PFCs do not deplete the stratospheric ozone layer, and are therefore acceptable alternatives under the *Montreal Protocol*.

These compounds, however, along with SF_6, are potent greenhouse gases. In addition to having high global warming potentials, SF_6 and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated.

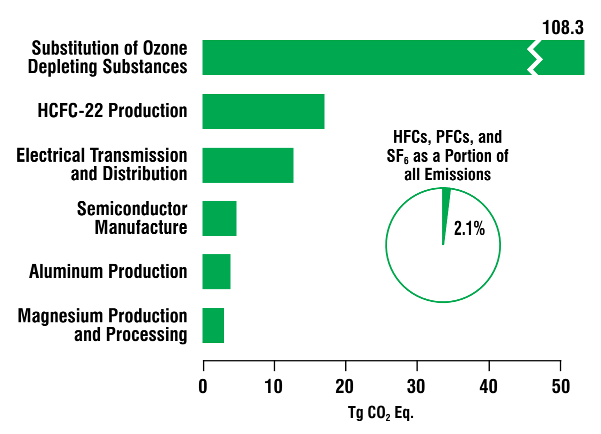
Other emissive sources of these gases include HCFC-22 production, electrical transmission and distribution systems, semiconductor manufacturing, aluminum production, and magnesium production and processing (see Figure ES-10).

Some significant trends in U.S. HFC, PFC, and SF_6 emissions include the following:

- Emissions resulting from the substitution of ozone depleting substances (e.g., CFCs) have been increasing from small amounts in 1990 to 108.3 Tg CO_2 Eq. in 2007. Emissions from substitutes for ozone depleting substances are both the largest and the fastest growing source of HFC, PFC, and SF_6 emissions. These emissions have been increasing as phase-outs

Figure ES-10

2007 Sources of HFCs, PFCs, and SF_6 Emissions



required under the *Montreal Protocol* come into effect, especially after 1994 when full market penetration was made for the first generation of new technologies featuring ODS substitutes.

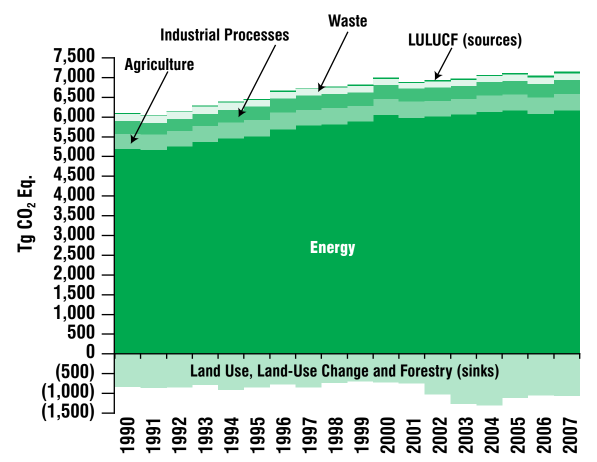
- HFC emissions from the production of HCFC-22 decreased by 53 percent (19.4 Tg CO_2 Eq.) from 1990 to 2007, due to a steady decline in the emission rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured) and the use of thermal oxidation at some plants to reduce HFC-23 emissions.
- SF_6 emissions from electric power transmission and distribution systems decreased by 53 percent (14.1 Tg CO_2 Eq.) from 1990 to 2007, primarily because of higher purchase prices for SF_6 and efforts by industry to reduce emissions.
- PFC emissions from aluminum production decreased by 79 percent (14.7 Tg CO_2 Eq.) from 1990 to 2007, due to both industry emission reduction efforts and lower domestic aluminum production.

ES.3. Overview of Sector Emissions and Trends

In accordance with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), and the 2003 *UNFCCC Guidelines on Reporting and Review* (UNFCCC 2003), Figure ES-11 and Table ES-4 aggregate emissions and sinks by these chapters.

Figure ES-11

U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector



Note: Relatively smaller amounts of GWP-weighted emissions are also emitted from the Solvent and Other Product Use sectors.

Emissions of all gases can be summed from each source category from Intergovernmental Panel on Climate Change (IPCC) guidance. Over the eighteen-year period of 1990 to 2007, total emissions in the Energy, Industrial Processes, and Agriculture sectors climbed by 976.7 Tg CO_2 Eq. (19 percent), 28.5 Tg CO_2 Eq. (9 percent), and 28.9 Tg CO_2 Eq. (8 percent), respectively. Emissions decreased in the Waste and Solvent and Other Product Use sectors by 11.5 Tg CO_2 Eq. (6 percent) and less than 0.1 Tg CO_2 Eq. (0.4 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 192.5 Tg CO_2 Eq. (23 percent).

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. CO_2 emissions for the period of 1990 through 2007. In 2007, approximately 85 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 15 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 CH_4 and N_2O emissions (35 percent and 14 percent of total U.S. emissions of each gas, respectively).

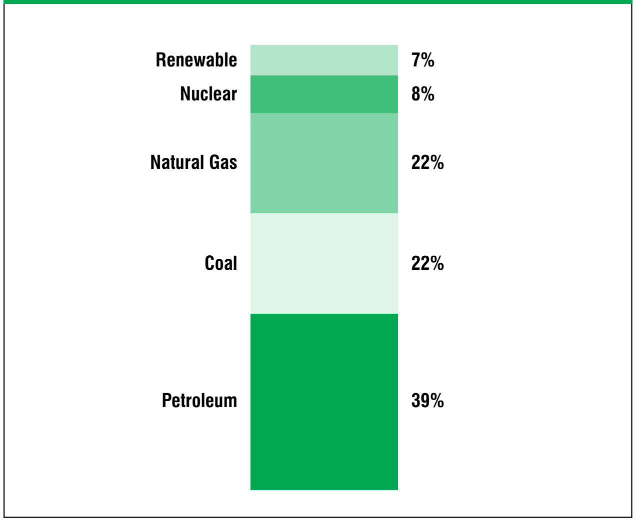
Table ES-4: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

Chapter/IPCC Sector	1990	1995	2000	2005	2006	2007
Energy	5,193.6	5,520.1	6,059.9	6,169.2	6,084.4	6,170.3
Industrial Processes	325.2	345.8	356.3	337.6	343.9	353.8
Solvent and Other Product Use	4.4	4.6	4.9	4.4	4.4	4.4
Agriculture	384.2	402.0	399.4	410.8	410.3	413.1
Land Use, Land-Use Change, and Forestry (Emissions)	14.2	16.2	33.0	26.4	45.1	42.9
Waste	177.1	174.7	154.6	160.2	163.0	165.6
Total Emissions	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Sinks)[a]	(841.4)	(851.0)	(717.5)	(1,122.7)	(1,050.5)	(1,062.6)
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-12

2007 U.S. Energy Consumption by Energy Source



Overall, emission sources in the Energy chapter account for a combined 86.3 percent of total U.S. greenhouse gas emissions in 2007.

Industrial Processes

The Industrial Processes chapter contains byproduct or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, and N_2O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production and urea consumption, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, and zinc production. Additionally, emissions from industrial processes release HFCs, PFCs, and SF_6. Overall, emission sources in the Industrial Processes chapter account for 4.9 percent of U.S. greenhouse gas emissions in 2007.

Solvent and Other Product Use

The Solvent and Other Product Use chapter contains greenhouse gas emissions that are produced as a by-product of various solvent and other product uses. In the United States, emissions from N_2O from product uses, the only source of greenhouse gas emissions from this sector, accounted for less than 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2007.

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 about 24 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2007. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions in 2007, accounting for 67 percent. In 2007, emission sources accounted for in the Agriculture chapter were responsible for 6 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 have resulted in a net uptake (sequestration) of C in the United States. Forests (including vegetation, soils, and harvested wood) accounted for approximately 86 percent of total 2007 net CO_2 flux, urban trees accounted for 9 percent, mineral and organic soil carbon stock changes accounted for 4 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2007. The net forest sequestration is a result of net forest growth and increasing forest area, as well as a net accumulation of carbon 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 70 percent more C than is emitted through these soils, liming, and urea fertilization, combined. 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. Land use, land-use change, and forestry activities in 2007 resulted in a net C sequestration of 1,062.6 Tg CO_2 Eq. (Table ES-5). This represents an offset of approximately 17.4 percent of total U.S. CO_2 emissions, or 14.9 percent of total greenhouse gas emissions in 2007. Between 1990 and 2007, total land use, land-use change, and forestry net C flux resulted in a 26.3 percent increase in CO_2 sequestration, primarily due to an increase in the rate of net C accumulation in forest C stocks, particularly in aboveground and belowground tree biomass. Annual C accumulation in landfilled yard trimmings and food

Table ES-5: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	2000	2005	2006	2007
Forest Land Remaining Forest Land	(661.1)	(686.6)	(512.6)	(975.7)	(900.3)	(910.1)
Cropland Remaining Cropland	(29.4)	(22.9)	(30.2)	(18.3)	(19.1)	(19.7)
Land Converted to Cropland	2.2	2.9	2.4	5.9	5.9	5.9
Grassland Remaining Grassland	(46.7)	(36.4)	(51.4)	(4.6)	(4.6)	(4.7)
Land Converted to Grassland	(22.3)	(22.5)	(32.0)	(26.7)	(26.7)	(26.7)
Settlements Remaining Settlements	(60.6)	(71.5)	(82.4)	(93.3)	(95.5)	(97.6)
Other (Landfilled Yard Trimmings and Food Scraps)	(23.5)	(13.9)	(11.3)	(10.2)	(10.4)	(9.8)
Total	**(841.4)**	**(851.0)**	**(717.5)**	**(1,122.7)**	**(1,050.5)**	**(1,062.6)**

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

Table ES-6: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	1990	1995	2000	2005	2006	2007
CO_2	**8.1**	**8.1**	**8.8**	**8.9**	**8.8**	**9.0**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.4	4.3	4.3	4.2	4.1
Cropland Remaining Cropland: Urea Fertilization	2.4	2.7	3.2	3.5	3.7	4.0
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.0	1.2	1.1	0.9	1.0
CH_4	**4.6**	**6.1**	**20.6**	**14.2**	**31.3**	**29.0**
Forest Land Remaining Forest Land: Forest Fires	4.6	6.1	20.6	14.2	31.3	29.0
N_2O	**1.5**	**2.0**	**3.6**	**3.3**	**5.0**	**4.9**
Forest Land Remaining Forest Land: Forest Fires	0.5	0.6	2.1	1.4	3.2	2.9
Forest Land Remaining Forest Land: Forest Soils	0.0	0.1	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils	1.0	1.2	1.2	1.5	1.5	1.6
Total	**14.2**	**16.2**	**33.0**	**26.4**	**45.1**	**42.9**

\+ Less than 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

scraps slowed over this period, while the rate of annual C accumulation increased in urban trees.

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table ES-6. The application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization resulted in CO_2 emissions of 8.0 Tg CO_2 Eq. in 2007, an increase of 13 percent relative to 1990. The application of synthetic fertilizers to forest and settlement soils in 2007 resulted in direct N_2O emissions of 1.6 Tg CO_2 Eq. Direct N_2O emissions from fertilizer application increased by approximately 61 percent between 1990 and 2007. Non-CO_2 emissions from forest fires in 2007 resulted in CH_4 emissions of 29.0 Tg CO_2 Eq., and in N_2O emissions of 2.9 Tg CO_2 Eq. CO_2 and N_2O emissions from peatlands totaled 1.0 Tg CO_2 Eq. and less than 0.01 Tg CO_2 Eq. in 2007, respectively.

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 CH_4 emissions in the Waste chapter, accounting for 23 percent of total U.S. CH_4 emissions.[13] Additionally, wastewater treatment accounts for 4 percent of U.S. CH_4 emissions. 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. Emissions of CH_4 and N_2O from composting grew from 1990 to 2007, and resulted in emissions of 1.7 Tg CO_2 Eq. and 1.8 Tg CO_2 Eq., respectively. Overall, in 2007, emission sources accounted for in the Waste chapter generated 2.3 percent of total U.S. greenhouse gas emissions.

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 six sectors (i.e., chapters) defined by the IPCC: Energy; Industrial Processes; Solvent Use; Agriculture; Land Use, Land-Use Change, and Forestry; and Waste. While it is

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[13] 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.

Table ES-7: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq.)

Implied Sectors	1990	1995	2000	2005	2006	2007
Electric Power Industry	1,859.1	1,989.0	2,329.3	2,429.4	2,375.5	2,445.1
Transportation	1,543.6	1,685.2	1,919.7	1,998.9	1,994.4	1,995.2
Industry	1,496.0	1,524.5	1,467.5	1,364.9	1,388.4	1,386.3
Agriculture	428.5	453.7	470.2	482.6	502.9	502.8
Commercial	392.9	401.0	388.2	401.8	392.6	407.6
Residential	344.5	368.8	386.0	370.5	334.9	355.3
U.S. Territories	34.1	41.1	47.3	60.5	62.3	57.7
Total Emissions	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Land Use, Land-Use Change, and Forestry (Sinks)	(841.4)	(851.0)	(717.5)	(1,122.7)	(1,050.5)	(1,062.6)
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

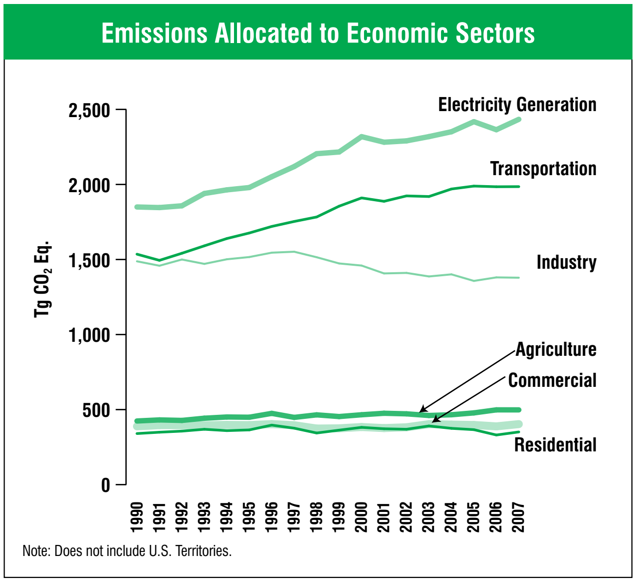
Note: Totals may not sum due to independent rounding. Emissions include CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. See Table 2-12 for more detailed data.

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-7 summarizes emissions from each of these sectors, and Figure ES-13 shows the trend in emissions by sector from 1990 to 2007.

Using this categorization, emissions from electricity generation accounted for the largest portion (34 percent) of U.S. greenhouse gas emissions in 2007. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Emissions from industry accounted for 20 percent of U.S. greenhouse gas emissions in 2007. 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 18 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 about 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 7 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion.

Figure ES-13



Note: Does not include U.S. Territories.

The commercial sector accounted for about 6 percent of emissions, while U.S. territories accounted for approximately 1 percent.

CO_2 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.

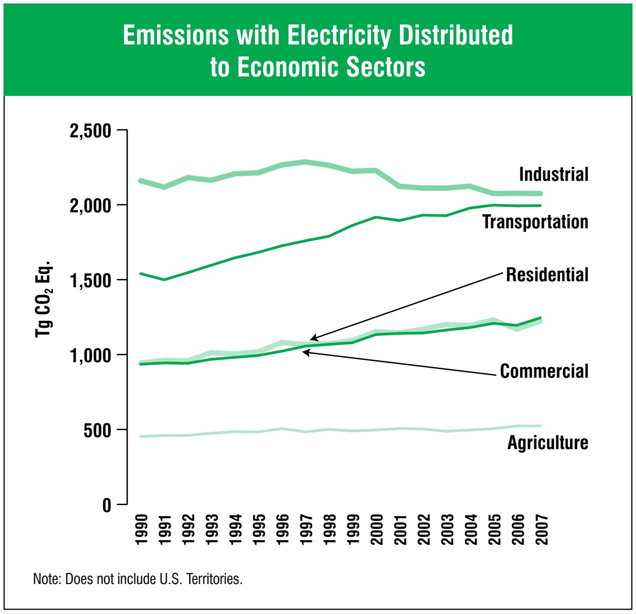
Electricity is ultimately consumed in the economic sectors described above. Table ES-8 presents greenhouse gas emissions from economic sectors with emissions related to electricity generation distributed into end-use categories (i.e., emissions from electricity generation are allocated to the economic sectors in which the electricity is consumed). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electricity

Table ES-8: U.S. Greenhouse Gas Emissions by Economic Sector with Electricity-Related Emissions Distributed (Tg CO_2 Eq.)

Implied Sectors	1990	1995	2000	2005	2006	2007
Industry	2,166.5	2,219.8	2,235.5	2,081.2	2,082.3	2,081.2
Transportation	1,546.7	1,688.3	1,923.2	2,003.6	1,999.0	2,000.1
Commercial	942.2	1,000.2	1,140.0	1,214.6	1,201.5	1,251.2
Residential	950.0	1,024.2	1,159.2	1,237.0	1,176.1	1,229.8
Agriculture	459.2	489.7	503.2	511.7	530.0	530.1
U.S. Territories	34.1	41.1	47.3	60.5	62.3	57.7
Total Emissions	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Land Use, Land-Use Change, and Forestry (Sinks)	(841.4)	(851.0)	(717.5)	(1,122.7)	(1,050.5)	(1,062.6)
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

See Table 2-14 for more detailed data.

Figure ES-14



Note: Does not include U.S. Territories.

generation were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity.[14] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (30 percent) in 2007. Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption (e.g., lighting, appliances, etc.). Transportation activities remain the second largest contributor to total U.S. emissions (28 percent). In all sectors except agriculture, CO_2 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 2007.

Indirect Greenhouse Gases (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[15] request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO_2. These gases do not have a direct global warming effect, but indirectly affect terrestrial radiation absorption by influencing the formation

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[14] 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.

[15] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

Box ES-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 nonutilities combined—was the largest source of U.S. greenhouse gas emissions in 2007; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table ES-9 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 0.9 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption and much slower than that for either electricity consumption or overall gross domestic product. Total U.S. greenhouse gas emissions have also grown slightly slower than national population since 1990 (see Figure ES-15).

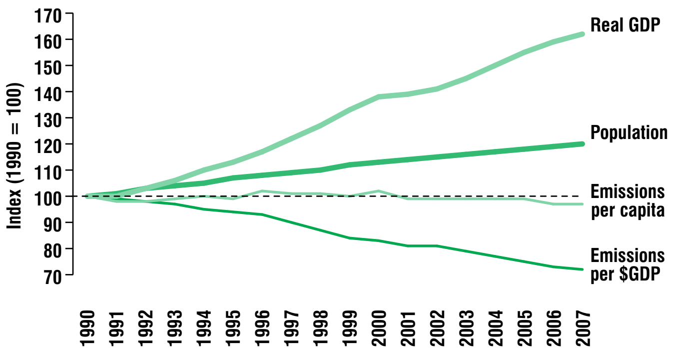
Table ES-9: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	1995	2000	2005	2006	2007	Growth Rate[a]
GDP[b]	100	113	138	155	159	162	2.9%
Electricity Consumption[c]	100	112	127	134	135	137	1.9%
Fossil Fuel Consumption[c]	100	107	117	119	117	119	1.1%
Energy Consumption[c]	100	108	117	119	118	120	1.1%
Population[d]	100	107	113	118	119	120	1.1%
Greenhouse Gas Emissions[e]	100	106	115	117	115	117	0.9%

[a] Average annual growth rate
[b] Gross Domestic Product in chained 2000 dollars (BEA 2008)
[c] Energy content-weighted values (EIA 2008a)
[d] U.S. Census Bureau (2008)
[e] GWP-weighted values

Figure ES-15

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2008), U.S. Census Bureau (2008), and emission estimates in this report.

Table ES-10: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	2000	2005	2006	2007
NO_x	**21,450**	**21,070**	**19,004**	**15,612**	**14,701**	**14,250**
Mobile Fossil Fuel Combustion	10,920	10,622	10,310	8,757	8,271	7,831
Stationary Fossil Fuel Combustion	9,689	9,619	7,802	5,857	5,445	5,445
Industrial Processes	591	607	626	534	527	520
Oil and Gas Activities	139	100	111	321	316	314
Incineration of Waste	82	88	114	98	98	97
Agricultural Burning	28	29	35	39	38	37
Solvent Use	1	3	3	5	5	5
Waste	0	1	2	2	2	2
CO	**130,461**	**109,032**	**92,776**	**71,672**	**67,453**	**63,875**
Mobile Fossil Fuel Combustion	119,360	97,630	83,559	62,519	58,322	54,678
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,778	4,792	4,792
Industrial Processes	4,125	3,959	2,216	1,744	1,743	1,743
Incineration of Waste	978	1,073	1,670	1,439	1,438	1,438
Agricultural Burning	691	663	792	860	825	892
Oil and Gas Activities	302	316	146	324	323	323
Waste	1	2	8	7	7	7
Solvent Use	5	5	45	2	2	2
NMVOCs	**20,930**	**19,520**	**15,227**	**14,562**	**14,129**	**13,747**
Mobile Fossil Fuel Combustion	10,932	8,745	7,229	6,292	5,954	5,672
Solvent Use	5,216	5,609	4,384	3,881	3,867	3,855
Industrial Processes	2,422	2,642	1,773	2,035	1,950	1,878
Stationary Fossil Fuel Combustion	912	973	1,077	1,450	1,470	1,470
Oil and Gas Activities	554	582	388	545	535	526
Incineration of Waste	222	237	257	243	239	234
Waste	673	731	119	115	113	111
Agricultural Burning	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,830**	**13,348**	**12,259**	**11,725**
Stationary Fossil Fuel Combustion	18,407	14,724	12,849	11,641	10,650	10,211
Industrial Processes	1,307	1,117	1,031	852	845	839
Mobile Fossil Fuel Combustion	793	672	632	600	520	442
Oil and Gas Activities	390	335	287	233	221	210
Incineration of Waste	38	42	29	22	22	22
Waste	0	1	1	1	1	1
Solvent Use	0	1	1	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA

NA (Not Available)
Note: Totals may not sum due to independent rounding.
Source: EPA (2008), disaggregated based on EPA (2003), except for estimates from field burning of agricultural residues.

and destruction of tropospheric and stratospheric ozone, or, in the case of SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases.

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2008),[16] which are regulated under the Clean Air Act. Table ES-10 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.

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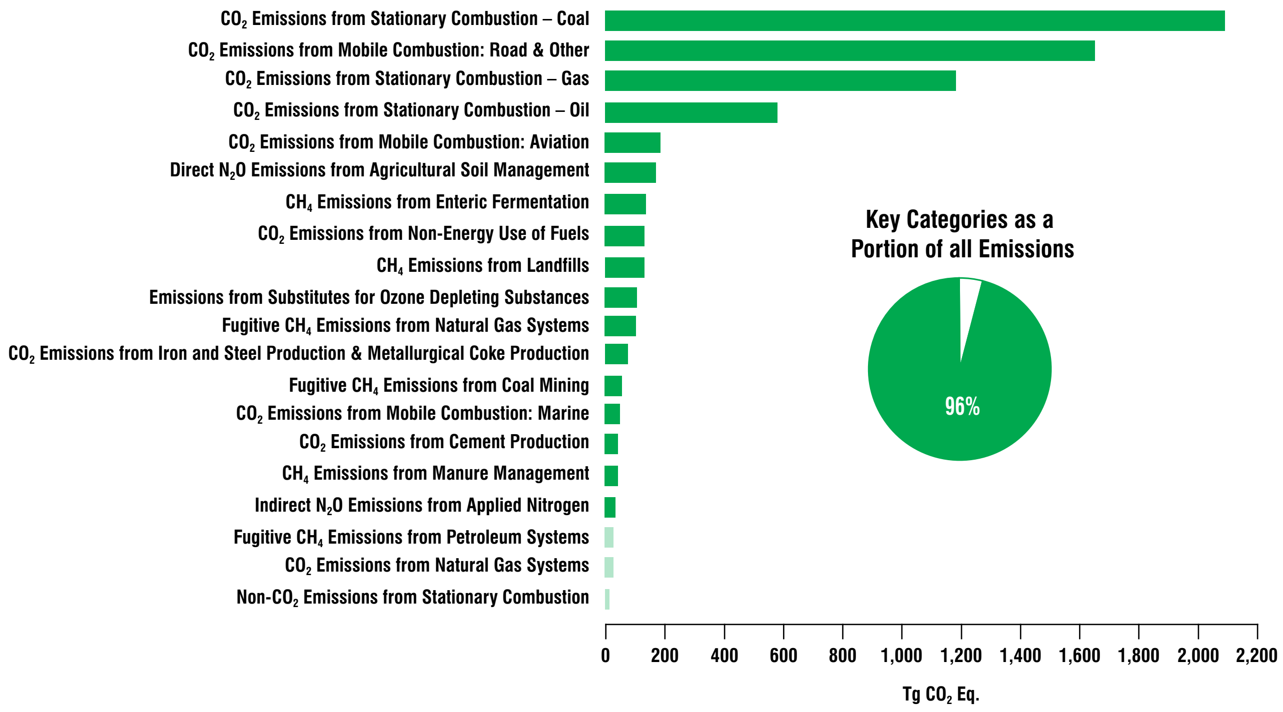
[16] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2008).

Figure ES-16

2007 Key Categories



Notes: For a complete discussion of the key source analysis, see Annex 1. Darker bars indicate a Tier 1 level assessment key category. Lighter bars indicate a Tier 2 level assessment key category.

Key Categories

The IPCC's Good Practice Guidance (IPCC 2000) defines a key category as a "[source or sink category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."[17] 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 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 2007 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. For more information regarding key categories, see Section 1.5 and Annex 1 of the Inventory.

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

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[17] See Chapter 7 "Methodological Choice and Recalculation" in IPCC (2000). <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

formalized in accordance with the QA/QC plan and the UNFCCC reporting guidelines.

Uncertainty Analysis of Emission Estimates

While the current U.S. emissions Inventory provides a solid foundation for the development of a more detailed and comprehensive national inventory, there are uncertainties associated with the emission estimates. Some of the current estimates, such as those for CO_2 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 *IPCC Good Practice Guidance* (IPCC 2000) 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.

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 2007. 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 basis in order to show the relative contribution of each gas to global average radiative forcing.[1] 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 accepted the *Revised 1996 IPCC Guidelines* at its Twelfth Session (Mexico City, September 11–13, 1996). This report presents information in accordance with these guidelines. In addition, this Inventory is in accordance with the IPCC *Good Practice Guidance and Uncertainty*

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[1] See the section below entitled *Global Warming Potentials* for an explanation of 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/UNEP/OECD/IEA 1997).

[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>.

Management in National Greenhouse Gas Inventories and the *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*, which further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines*. The IPCC has also accepted the *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) at its Twenty-Fifth Session (Mauritius, April 2006). The *2006 IPCC Guidelines* build on the previous bodies of work and includes 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." Many of the methodological improvements presented in the *2006 Guidelines* have been adopted in this Inventory.

Overall, this Inventory of anthropogenic greenhouse gas emissions 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 structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2006).

1.1. Background Information

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), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the earth (IPCC 2001). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans.[5] A gauge of these changes is called radiative forcing, which is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the earth-atmosphere system (IPCC 2001). 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).

> *Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).*

Naturally occurring greenhouse gases include water vapor, CO_2, methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in national greenhouse gas inventories.[6] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—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 gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases 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 that are often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants. They can affect the absorptive characteristics of the atmosphere. Comparatively, however, the level of scientific understanding of aerosols is still very low (IPCC 2001).

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[5] For more on the science of climate change, see NRC (2001).

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

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

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	278 ppm	0.715 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	379 ppm	1.774 ppm	0.319 ppm	5.6 ppt	74 ppt
Rate of concentration change	1.4 ppm/yr	0.005 ppm/yr[a]	0.26% yr	Linear[b]	Linear[b]
Atmospheric lifetime[c]	50–200[d]	12[e]	114[e]	3,200	>50,000

[a] The growth rate for atmospheric CH_4 has been decreasing from 14 ppb/yr in 1984 to almost 0 ppb/yr in 2001, 2004, and 2005 (IPCC 2007).
[b] IPCC (2007) identifies the rate of concentration change for SF_6 and CF_4 as linear.
[c] Source: IPCC (1996).
[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.
[e] 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, current atmospheric concentrations, and rate of concentration changes for all gases are from IPCC (2007).
Note: ppt (parts per thousand), ppm (parts per million), ppb (parts per billion).

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.

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). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to affect directly the average global concentration of water vapor, but the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. While a warmer atmosphere has an increased water holding capacity, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide. 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 379 ppmv in 2005, a 35 percent increase (IPCC 2007 and Hofmann 2004).[7,8] The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). 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.

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[7] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2001).

[8] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750-1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2001).

In its second assessment, the IPCC also stated that "[t]he increased amount of CO_2 [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the earth's surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane. 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 143 percent since 1750, from a pre-industrial value of about 722 ppb to 1,774 ppb in 2005, although the rate of increase has been declining. 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 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 may increase the atmospheric lifetime of CH_4 (IPCC 2001).

Nitrous Oxide. Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 18 percent since 1750, from a pre-industrial value of about 270 ppb to 319 ppb in 2005, 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. Ozone is present in both the upper stratosphere,[9] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[10] 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 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds 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 2001)

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride. 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 [HFCs]) 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

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[9] 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.

[10] 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.

harmful levels of ultraviolet radiation. Under the *Montreal Protocol,* the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5[11] 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.

HFCs, PFCs, and SF_6 are not ozone depleting substances, and therefore are not covered under the *Montreal Protocol*. They are, however, powerful greenhouse gases. HFCs 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 2001). PFCs and SF_6 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 and SF_6 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 2001).

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

Nitrogen Oxides. The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects.[12] Additionally, NO_x emissions from aircraft are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Non-CH_4 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. They can be produced by natural events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. Aerosols affect radiative forcing differently than greenhouse gases, and their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols is typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect

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[11] 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.

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

involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulfates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous[13] aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols on radiative forcing is believed to be negative (i.e., net cooling effect on the climate), although because they remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[14] Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). "However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result" (IPCC 1996).

The IPCC's *Third Assessment Report* notes that "the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive" (IPCC 2001). Additionally, current research suggests that another constituent of aerosols, black carbon, may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of black carbon include diesel exhaust and open biomass burning.

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 2001). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference gas used is CO_2, and therefore GWP weighted emissions are measured in teragrams of CO_2 equivalent (Tg CO_2 Eq.).[15] The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg CO}_2\text{ Eq.} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\text{ Gg}}\right)$$

where,

Tg CO_2 Eq.	=	Teragrams of CO_2 Equivalents
Gg	=	Gigagrams (equivalent to a thousand metric tons)
GWP	=	Global Warming Potential
Tg	=	Teragrams

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. The parties to the UNFCCC have also agreed to use GWPs based upon a 100-year time horizon although other time horizon values are available.

> *Greenhouse gas emissions and removals should be presented on a gas-by-gas basis in units of mass... In addition, consistent with decision 2/CP.3, Parties should report aggregate emissions and removals of greenhouse gases, expressed in CO_2 equivalent terms at summary inventory level, using GWP values provided by the IPCC in its Second Assessment Report... based on the effects of greenhouse gases over a 100-year time horizon.*[16]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be

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[13] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2001).

[14] Volcanic activity can inject significant quantities of aerosol-producing SO_2 and other sulfur compounds into the stratosphere, which can result in a longer negative forcing effect (i.e., a few years) (IPCC 1996).

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

[16] Framework Convention on Climate Change; <http://unfccc.int/resource/docs/cop8/08.pdf>; 1 November 2002; Report of the Conference of the Parties at its eighth session; held at New Delhi from 23 October to 1 November 2002; Addendum; Part One: Action taken by the Conference of the Parties at its eighth session; Decision -/CP.8; Communications from Parties included in Annex I to the Convention: Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, Part 1: UNFCCC reporting guidelines on annual inventories; p. 7. (UNFCCC 2003).

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

Gas	Atmospheric Lifetime	GWP[a]
CO_2	50–200	1
CH_4[b]	12±3	21
N_2O	120	310
HFC-23	264	11,700
HFC-32	5.6	650
HFC-125	32.6	2,800
HFC-134a	14.6	1,300
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-227ea	36.5	2,900
HFC-236fa	209	6,300
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

[a] 100-year time horizon

[b] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Source: (IPCC 1996)

determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. No GWP values are attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

1.2. Institutional 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, 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. The 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 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 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.

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

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

In 2007, the IPCC published its *Fourth Assessment Report* (AR4), which provided an updated and more comprehensive scientific assessment of climate change. Within this report, the GWPs of several gases were revised relative to the SAR and the IPCC's *Third Assessment Report* (TAR) (IPCC 2001). Thus the GWPs used in this report have been updated twice by the IPCC; although the SAR GWPs are used throughout this report, it is interesting to review the changes to the GWPs and the impact such improved understanding has on the total GWP-weighted emissions of the United States. Since the SAR and TAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function. The GWPs are drawn from IPCC/TEAP (2005) and the TAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. In addition, the values for radiative forcing and lifetimes have been recalculated for a variety of halocarbons, which were not presented in the SAR. Table 1-3 presents the new GWPs, relative to those presented in the SAR.

Table 1-3: Comparison of 100-Year GWPs

Gas	SAR	TAR	AR4	Change from SAR	
				TAR	AR4
CO_2	1	1	1	NC	0
CH_4[a]	21	23	25	2	4
N_2O	310	296	298	(14)	(12)
HFC-23	11,700	12,000	14,800	300	3,100
HFC-32	650	550	675	(100)	25
HFC-125	2,800	3,400	3,500	600	700
HFC-134a	1,300	1,300	1,430	NC	130
HFC-143a	3,800	4,300	4,470	500	670
HFC-152a	140	120	124	(20)	(16)
HFC-227ea	2,900	3,500	3,220	600	320
HFC-236fa	6,300	9,400	9,810	3,100	3,510
HFC-4310mee	1,300	1,500	1,640	200	340
CF_4	6,500	5,700	7,390	(800)	890
C_2F_6	9,200	11,900	12,200	2,700	3,000
C_4F_{10}	7,000	8,600	8,860	1,600	1,860
C_6F_{14}	7,400	9,000	9,300	1,600	1,900
SF_6	23,900	22,200	22,800	(1,700)	(1,100)

NC (No Change)

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Note: Parentheses indicate negative values.

Source: IPCC (2001, 2007)

To comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. The UNFCCC reporting guidelines for national inventories[17] were updated in 2002 but continue to require the use of GWPs from the SAR so that current estimates of aggregate greenhouse gas emissions for 1990 through 2006 are consistent and comparable with estimates developed prior to the publication of the TAR and AR4. For informational purposes, emission estimates that use the updated GWPs are presented in detail in Annex 6.1 of this report. All estimates provided throughout this report are also presented in unweighted units.

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[17] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

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 CRF, 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 IPCC *Good Practice Guidance,* IPCC *Good Practice Guidance for Land Use, Land Use Change and Forestry,* 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 for printing, posted online, printed by the U.S. Government Printing Office, and made available for the public.

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 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997). In addition, the United States references the additional guidance provided in the IPCC *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC 2000), the IPCC *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003), and 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 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 *Revised 1996 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 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 1-2: IPCC Reference Approach

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology. 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 IPCC's *Good Practice Guidance* (IPCC 2000) defines a key category as a "[source or sink category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."[18] By definition, key categories include those sources that have the greatest contribution to the absolute level of national emissions. 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 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 either of the quantitative analyses.

A Tier 1 approach, as defined in the IPCC's *Good Practice Guidance* (IPCC 2000), 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 the Tier 1 approach, a Tier 2 approach, as defined in the IPCC's *Good Practice Guidance* (IPCC 2000), was then implemented to identify any additional key categories not already identified in the Tier 1 assessment. This analysis, which includes each source cateogory's uncertainty assessments in its calculations, was also performed twice to include or exclude LULUCF sources.

In addition to conducting Tier 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the IPCC's *Good Practice Guidance* (IPCC 2000), 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 with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to the Tier 1 approach. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key, which would qualify it as a key category according to the Tier 2 approach.

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-weighted emissions in 2007. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Tier 1, Tier 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.

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. QA/QC plan, *Quality Assurance/Quality Control and Uncertainty Management Plan for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

In particular, key attributes of the QA/QC plan include:

- specific detailed procedures and forms 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 the uncertainty of the inventory estimates;
- expert review as well as QC—for both the inventory estimates and the Inventory (which is the primary vehicle for disseminating the results of the inventory development process). In addition, the plan provides for public review of the Inventory;

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[18] See Chapter 7 "Methodological Choice and Recalculation" in IPCC (2000). <http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm>

Table 1-4: Key Categories for the United States (1990–2007)

IPCC Source Categories	Gas	Tier 1				Tier 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	Qual[a]	2007 Emissions (Tg CO_2 Eq.)
Energy											
CO_2 Emissions from Stationary Combustion-Coal	CO_2	✓	✓	✓	✓	✓	✓	✓	✓		2,086.5
CO_2 Emissions from Mobile Combustion: Road & Other	CO_2	✓	✓	✓	✓	✓	✓	✓	✓		1,649.1
CO_2 Emissions from Stationary Combustion-Gas	CO_2	✓	✓	✓	✓	✓	✓	✓			1,181.1
CO_2 Emissions from Stationary Combustion-Oil	CO_2	✓	✓	✓	✓	✓	✓	✓	✓		580.4
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	✓	✓	✓	✓	✓		✓			187.5
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	✓		✓		✓		✓			133.9
CO_2 Emissions from Mobile Combustion: Marine	CO_2	✓		✓							50.8
CO_2 Emissions from Natural Gas Systems	CO_2	✓	✓	✓	✓	✓	✓	✓	✓		28.7
CO_2 Emissions from Incineration of Waste	CO_2		✓		✓						20.8
Fugitive CH_4 Emissions from Natural Gas Systems	CH_4	✓	✓	✓	✓	✓	✓	✓	✓		104.7
Fugitive CH_4 Emissions from Coal Mining	CH_4	✓	✓	✓	✓	✓	✓	✓	✓		57.6
Fugitive CH_4 Emissions from Petroleum Systems	CH_4	✓	✓	✓	✓	✓	✓	✓	✓		28.8
Non-CO_2 Emissions from Stationary Combustion	CH_4						✓				6.6
N_2O Emissions from Mobile Combustion: Road & Other	N_2O	✓	✓	✓	✓		✓		✓		27.9
Non-CO_2 Emissions from Stationary Combustion	N_2O					✓		✓			14.7
International Bunker Fuels[b]	Several									✓	109.9
Industrial Processes											
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	✓	✓	✓	✓	✓	✓	✓	✓		77.4
CO_2 Emissions from Cement Production	CO_2	✓		✓							44.5
CO_2 Emissions from Ammonia Production and Urea Consumption	CO_2		✓		✓						13.8
N_2O Emissions from Adipic Acid Production	N_2O		✓		✓						5.9
Emissions from Substitutes for Ozone Depleting Substances	Several	✓	✓	✓	✓		✓		✓		108.3
HFC-23 Emissions from HCFC-22 Production	HFCs	✓	✓	✓	✓		✓				17.0
SF_6 Emissions from Electrical Transmission and Distribution	SF_6		✓		✓		✓		✓		12.7
PFC Emissions from Aluminum Production	PFCs		✓		✓						3.8
Agriculture											
CH_4 Emissions from Enteric Fermentation	CH_4	✓	✓	✓	✓	✓	✓	✓	✓		139.0
CH_4 Emissions from Manure Management	CH_4	✓	✓	✓	✓						44.0
CH_4 Emissions from Rice Cultivation	CH_4						✓		✓		6.2
Direct N_2O Emissions from Agricultural Soil Management	N_2O	✓	✓	✓	✓	✓	✓	✓	✓		172.0
Indirect N_2O Emissions from Applied Nitrogen	N_2O	✓	✓	✓	✓	✓	✓	✓	✓		35.9
Waste											
CH_4 Emissions from Landfills	CH_4	✓	✓	✓	✓	✓	✓	✓	✓		132.9
CH_4 Emissions from Wastewater Treatment	CH_4							✓			24.4

Table 1-4: Key Categories for the United States (1990–2007) (continued)

IPCC Source Categories	Gas	Tier 1				Tier 2				Qual[a]	2007 Emissions (Tg CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF		
Land Use, Land Use Change, and Forestry											
CO_2 from Changes in Forest Carbon Stocks	CO_2			✓	✓			✓	✓		-910.1
CO_2 Emissions from Urban Trees	CO_2			✓	✓			✓	✓		-97.6
CO_2 Emissions from Cropland Remaining Cropland	CO_2				✓			✓	✓		-11.6
CO_2 Emissions from Landfilled Yard Trimmings and Food Scraps	CO_2				✓			✓	✓		-9.8
CO_2 Emissions from Grassland Remaining Grassland	CO_2			✓	✓			✓	✓		-4.7
CH_4 Emissions from Forest Fires	CH_4			✓	✓			✓	✓		29.0
N_2O Emissions from Forest Fires	N_2O								✓		2.9
Subtotal Without LULUCF											**6,972.3**
Total Emissions Without LULUCF											**7,107.2**
Percent of Total Without LULUCF											**98%**
Subtotal With LULUCF											**5,991.9**
Total Emissions With LULUCF											**6,087.5**
Percent of Total With LULUCF											**98%**

[a] Qualitative criteria.

[b] Emissions from this source not included in totals.

- both Tier 1 (general) and Tier 2 (source-specific) quality controls and checks, as recommended by IPCC *Good Practice Guidance*;
- consideration of secondary data quality and source-specific quality checks (Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates provides for more structured communication and integration with the suppliers of secondary information;
- record-keeping provisions to track which procedures have been followed, and the results of the QA/QC and uncertainty analysis, and contains feedback mechanisms for corrective action based on the results of the investigations, thereby providing for continual data quality improvement and guided research efforts;
- implementation 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;
- a schedule for multi-year implementation; and
- promotion of coordination and interaction 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 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.

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 CO_2 emissions from energy-related activities and cement processing, 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. Despite these uncertainties, the UNFCCC reporting guidelines follow the recommendation in the *1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) and require that countries provide single point estimates of uncertainty 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

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

Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)		Mean[b] (Tg CO_2 Eq.)	Standard Deviation (Tg CO_2 Eq.)
		Lower Bound[c]	Upper Bound[c]	Lower Bound[c]	Upper Bound[c]		
CO_2	6,103.4	5,974.9	6,390.0	-2%	+5%	6,181.5	106.8
CH_4	585.3	527.0	689.0	-10%	+18%	599.3	41.3
N_2O	311.9	278.7	440.6	-11%	+41%	352.4	42.8
PFCs, HFCs & SF_6[d]	149.5	141.6	160.3	-5%	+7%	148.1	4.7
Total	**7,150.1**	**7,047.8**	**7,525.1**	**-1%**	**+5%**	**7,281.3**	**121.9**
Net Emissions (Sources and Sinks)	**6,087.5**	**5,917.7**	**6,503.9**	**-3%**	**+7%**	**6,205.6**	**150.1**

[a] The emission estimates correspond to a 95 percent confidence interval.

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

[c] The low and high estimates for total emissions were separately calculated through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

[d] The overall uncertainty estimate did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the inventory emission calculations for 2007.

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 CH_4 and N_2O 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 SF_6 from electrical transmission and distribution is limited due to a lack of activity data regarding national SF_6 consumption or average equipment leak rates.

The overall uncertainty estimate for the U.S. Greenhouse Gas Emissions Inventory was developed using the IPCC Tier 2 uncertainty estimation methodology. An estimate of the overall quantitative uncertainty is shown in Table 1-5.

The IPCC provides good practice guidance on two approaches—Tier 1 and Tier 2—to estimating uncertainty for individual source categories. Tier 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. Consistent with the IPCC *Good Practice Guidance*, over a multi-year timeframe, the United States expects to continue to improve the uncertainty estimates presented in this report.

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 uncertainties associated with 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 Reporter, 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 2007. Although this report is intended to be comprehensive, certain sources have been identified yet 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 made, new emission sources are quantified and included in the Inventory. For a complete list of sources excluded, see Annex 5 of this report.

1.9. Organization of Report

In accordance with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), and the *2003 UNFCCC Guidelines on Reporting and Review* (UNFCCC 2003), this Inventory of U.S. Greenhouse Gas Emissions and Sinks is segregated into six 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.

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

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.
Industrial Processes	Byproduct or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities such as fossil fuel combustion.
Solvent and Other Product Use	Emissions, of primarily NMVOCs, resulting from the use of solvents and N_2O from product uses.
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_2O from forest management, other land-use activities, and land-use change.
Waste	Emissions from waste management activities.

Source: IPCC/UNEP/OECD/IEA (1997)

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 CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy-consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-7.

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_2O, and Indirect Greenhouse Gases from Stationary Combustion
- 3.2. Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
- 3.3. Methodology for Estimating CH_4 Emissions from Coal Mining
- 3.4. Methodology for Estimating CH_4 Emissions from Natural Gas Systems
- 3.5. Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
- 3.6. Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
- 3.7. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
- 3.8. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
- 3.9. Methodology for Estimating CH_4 Emissions from Enteric Fermentation
- 3.10. Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
- 3.11. Methodology for Estimating N_2O Emissions from Agricultural Soil Management
- 3.12. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands
- 3.13. Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils on Croplands and Grasslands
- 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 Excluded

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
- 7.4. Additional Information on Uncertainty Analyses by Source

2. Trends in Greenhouse Gas Emissions

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

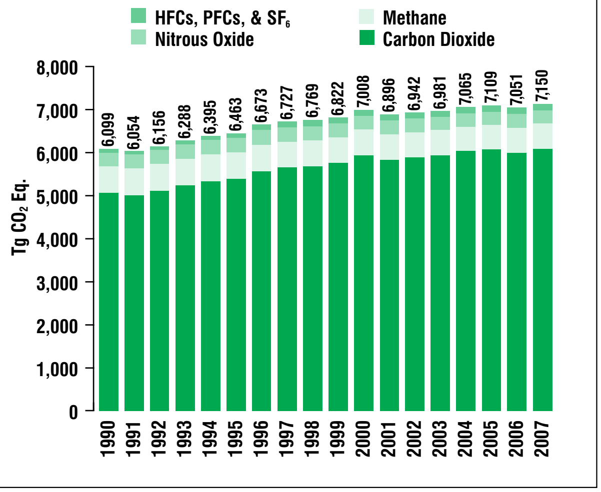
In 2007, total U.S. greenhouse gas emissions were 7,150.1 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.).[1] Overall, total U.S. emissions have risen by 17 percent from 1990 to 2007. Emissions increased from 2006 to 2007 by 1.4 percent (99.0 Tg CO_2 Eq.). The following factors were primary contributors to this increase: (1) cooler winter and warmer summer conditions in 2007 than in 2006 increased the demand for heating fuels and contributed to the increase in the demand for electricity; (2) increased consumption of fossil fuels to generate electricity; and (3) a significant decrease (14.2 percent) in hydropower generation used to meet this demand. Figure 2-1 through Figure 2-3 illustrate the overall trends in total U.S. emissions by gas,[2] annual changes, and absolute changes since 1990.

As the largest source of U.S. greenhouse gas emissions, carbon dioxide (CO_2) from fossil fuel combustion has accounted for approximately 79 percent of global warming potential (GWP) weighted emissions since 1990, growing slowly from 77 percent of total GWP-weighted emissions in 1990 to 80 percent in 2007. Emissions from this source category grew by 21.8 percent (1,026.9 Tg CO_2 Eq.) from 1990 to 2007 and were responsible for most of the increase in national emissions during this period. From 2006 to 2007, these emissions increased by 1.8 percent (100.4 Tg CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the dominant factor affecting U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors, including population and economic growth, energy price fluctuations, technological changes, and seasonal temperatures. On an annual basis, the overall consumption of fossil fuels in the United States 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

Figure 2-1

U.S. Greenhouse Gas Emissions by Gas



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

[2] See the following section for an analysis of emission trends by general U.S. economic sector.

Figure 2-2

Annual Percent Change in U.S. Greenhouse Gas Emissions

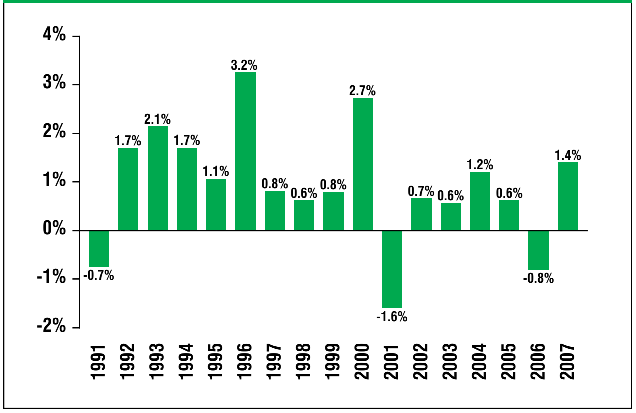
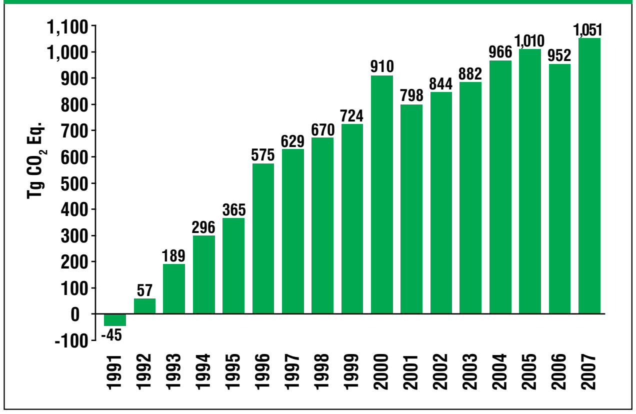


Figure 2-3

Cumulative Change in Annual U.S. Greenhouse Gas Emissions Relative to 1990



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 consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

Energy-related CO_2 emissions also depend on the type of fuel or energy consumed and its carbon (C) intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, can reduce the CO_2 emissions because of the lower C content of natural gas.

Emissions from fuel combustion increased in 2003 at about the average annual growth rate since 1990 (1.4 percent). A number of factors played a major role in the magnitude of this increase. The U.S. economy experienced moderate growth from 2002, causing an increase in the demand for fuels. The price of natural gas escalated dramatically, causing some electric power producers to switch to coal, which remained at relatively stable prices. Colder winter conditions brought on more demand for heating fuels, primarily in the residential sector. Though a cooler summer partially offset demand for electricity as the use of air-conditioners decreased, electricity consumption continued to increase in 2003. The primary drivers behind this trend were the growing economy and the increase in U.S. housing stock. Nuclear capacity decreased slightly, for the first time since 1997. Use of renewable fuels rose slightly due to increases in the use of hydroelectric power and biofuels.

From 2003 to 2004, these emissions continued to increase at about the average annual growth rate since 1990. A primary reason behind this trend was strong growth in the U.S. economy and industrial production, particularly in energy-intensive industries, causing an increase in the demand for electricity and fossil fuels. Demand for travel was also higher, causing an increase in petroleum consumed for transportation. In contrast, the warmer winter conditions led to decreases in demand for heating fuels, principally natural gas, in both the residential and commercial sectors. Moreover, much of the increased electricity demanded was generated by natural gas combustion and nuclear power, which moderated the increase in CO_2 emissions from electricity generation. Use of renewable fuels rose very slightly due to increases in the use biofuels.

Emissions from fuel combustion increased from 2004 to 2005 at a rate slightly lower than the average annual growth rate since 1990. A number of factors played a role in this slight increase. This small increase is primarily a result of the restraint on fuel consumption, primarily in the transportation sector, caused by rising fuel prices. Although electricity prices increased slightly, there was a significant increase in electricity consumption in the residential and commercial sectors due to warmer summer weather conditions. This led to an increase in emissions in these sectors with the increased use of air-conditioners. As electricity emissions increased among all end-use sectors, the fuels used to generate electricity increased as well. Despite a slight decrease in industrial energy-related emissions, industrial production and manufacturing output actually increased. The price of natural gas escalated dramatically, causing a decrease in consumption of natural gas in the industrial sector. Use of renewable fuels decreased slightly due to decreased use of biofuels and decreased electricity output by hydroelectric power plants.

From 2005 to 2006, emissions from fuel combustion decreased for the first time since 2000 to 2001. This decrease occurred primarily in the electricity generation, transportation, residential, and commercial sectors due to a number of factors. The decrease in emissions from electricity generation is a result of a smaller share of electricity generated by coal and a greater share generated by natural gas. Coal and natural gas consumption for electricity generation increased by 1.3 percent and 5.9 percent in 2006, respectively, and nuclear power increased by less than 1 percent. The transportation decrease is primarily a result of the restraint on fuel consumption caused by rising fuel prices, which directly resulted in a decrease of petroleum consumption within this sector of less than one percent in 2006. The decrease in emissions from the residential sector is primarily a result of decreased electricity consumption due to increases in the price of electricity, and warmer winter weather conditions. The increase in emissions in the industrial sector is a result of a increased emissions from fossil fuel combustion for this sector. A moderate increase in the industrial sector is a result of growth in industrial output and growth in the U.S. economy. Renewable fuels used to generate electricity increased in 2006, with the greatest growth occurring in wind.

After experiencing a decrease from 2005 to 2006, emissions from fuel combustion grew from 2006 to 2007 at a rate slightly higher than the average growth rate since 1990. There were a number of factors contributing to this increase. Unfavorable weather conditions in both the winter and summer resulted in an increase in consumption of heating fuels, as well as an increase in the demand for electricity. This demand for electricity was met with an increase in coal consumption of 1.8 percent, and with an increase in natural gas consumption of 10.3 percent. This increase in fossil fuel consumption, combined with a 14.2 percent decrease in hydropower generation from 2006 to 2007, resulted in an increase in emissions in 2007. The increase in emissions from the residential and commercial sectors is a result of increased electricity consumption due to warmer summer conditions and cooler winter conditions compared to 2006. In addition to these unfavorable weather conditions, electricity prices remained relatively stable compared to 2006, and natural gas prices decreased slightly. Emissions from the industrial sector increased slightly compared to 2006 as a result of a 1.7 percent increase in industrial production and the increase in fossil fuels used for electricity generation. Despite an overall decrease in electricity generation from renewable energy in 2007 driven by decreases in hydropower generation, wind and solar generation increased significantly.

Overall, from 1990 to 2007, total emissions of CO_2 increased by 1,026.7 Tg CO_2 Eq. (20.2 percent), while CH_4 and N_2O emissions decreased by 31.2 Tg CO_2 Eq. (5.1 percent) and 3.1 Tg CO_2 Eq. (1 percent) respectively. During the same period, aggregate weighted emissions of HFCs, PFCs, and SF_6 rose by 59 Tg CO_2 Eq. (65.2 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, and SF_6 are significant because many of them have extremely high GWPs and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by C sequestration in managed forests, trees in urban areas, agricultural soils, and landfilled yard trimmings, which was estimated to be 14.9 percent of total emissions in 2007.

Table 2-1 summarizes emissions and sinks from all U.S. anthropogenic sources in weighted units of Tg CO_2 Eq., while unweighted gas emissions and sinks in gigagrams (Gg) are provided in Table 2-2.

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

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**5,076.7**	**5,407.9**	**5,955.2**	**6,090.8**	**6,014.9**	**6,103.4**
Fossil Fuel Combustion	4,708.9	5,013.9	5,561.5	5,723.5	5,635.4	5,735.8
Electricity Generation	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
Transportation	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Industrial	834.2	862.6	844.6	828.0	844.5	845.4
Residential	337.7	354.4	370.4	358.0	321.9	340.6
Commercial	214.5	224.4	226.9	221.8	206.0	214.4
U.S. Territories	28.3	35.0	36.2	53.2	54.8	50.8
Non-Energy Use of Fuels	117.0	137.5	144.5	138.1	145.1	133.9
Iron and Steel Production & Metallurgical Coke Production	109.8	103.1	95.1	73.2	76.1	77.4
Cement Production	33.3	36.8	41.2	45.9	46.6	44.5
Natural Gas Systems	33.7	33.8	29.4	29.5	29.5	28.7
Incineration of Waste	10.9	15.7	17.5	19.5	19.8	20.8
Lime Production	11.5	13.3	14.1	14.4	15.1	14.6
Ammonia Production and Urea Consumption	16.8	17.8	16.4	12.8	12.3	13.8
Cropland Remaining Cropland	7.1	7.0	7.5	7.9	7.9	8.0
Limestone and Dolomite Use	5.1	6.7	5.1	6.8	8.0	6.2
Aluminum Production	6.8	5.7	6.1	4.1	3.8	4.3
Soda Ash Production and Consumption	4.1	4.3	4.2	4.2	4.2	4.1
Petrochemical Production	2.2	2.8	3.0	2.8	2.6	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.8	1.9	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	1.3	1.7	1.9
Ferroalloy Production	2.2	2.0	1.9	1.4	1.5	1.6
Phosphoric Acid Production	1.5	1.5	1.4	1.4	1.2	1.2
Wetlands Remaining Wetlands	1.0	1.0	1.2	1.1	0.9	1.0
Zinc Production	0.9	1.0	1.1	0.5	0.5	0.5
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(841.4)*	*(851.0)*	*(717.5)*	*(1,122.7)*	*(1,050.5)*	*(1,062.6)*
Biomass—Wood[b]	*215.2*	*229.1*	*218.1*	*208.9*	*209.9*	*209.8*
International Bunker Fuels[b]	*114.3*	*101.6*	*99.0*	*111.5*	*110.5*	*108.8*
Biomass—Ethanol[b]	*4.2*	*7.7*	*9.2*	*22.6*	*30.5*	*38.0*
CH_4	**616.6**	**615.8**	**591.1**	**561.7**	**582.0**	**585.3**
Enteric Fermentation	133.2	143.6	134.4	136.0	138.2	139.0
Landfills	149.2	144.3	122.3	127.8	130.4	132.9
Natural Gas Systems	129.6	132.6	130.8	106.3	104.8	104.7
Coal Mining	84.1	67.1	60.5	57.1	58.4	57.6
Manure Management	30.4	34.5	37.9	41.8	41.9	44.0
Forest Land Remaining Forest Land	4.6	6.1	20.6	14.2	31.3	29.0
Petroleum Systems	33.9	32.0	30.3	28.3	28.3	28.8
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4
Stationary Combustion	7.4	7.1	6.6	6.7	6.3	6.6
Rice Cultivation	7.1	7.6	7.5	6.8	5.9	6.2
Abandoned Underground Coal Mines	6.0	8.2	7.4	5.6	5.5	5.7
Mobile Combustion	4.7	4.3	3.4	2.5	2.4	2.3
Composting	0.3	0.7	1.3	1.6	1.6	1.7

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

Gas/Source	1990	1995	2000	2005	2006	2007
Petrochemical Production	0.9	1.1	1.2	1.1	1.0	1.0
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.9	0.8	0.9
Iron and Steel Production & Metallurgical Coke Production	1.0	1.0	0.9	0.7	0.7	0.7
Ferroalloy Production	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**315.0**	**334.1**	**329.2**	**315.9**	**312.1**	**311.9**
Agricultural Soil Management	200.3	202.3	204.5	210.6	208.4	207.9
Mobile Combustion	43.7	53.7	52.8	36.7	33.5	30.1
Nitric Acid Production	20.0	22.3	21.9	18.6	18.2	21.7
Manure Management	12.1	12.9	14.0	14.2	14.6	14.7
Stationary Combustion	12.8	13.3	14.5	14.8	14.5	14.7
Adipic Acid Production	15.3	17.3	6.2	5.9	5.9	5.9
Wastewater Treatment	3.7	4.0	4.5	4.8	4.8	4.9
N_2O from Product Uses	4.4	4.6	4.9	4.4	4.4	4.4
Forest Land Remaining Forest Land	0.5	0.8	2.4	1.8	3.5	3.3
Composting	0.4	0.8	1.4	1.7	1.8	1.8
Settlements Remaining Settlements	1.0	1.2	1.2	1.5	1.5	1.6
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.5	0.5
Incineration of Waste	0.5	0.5	0.4	0.4	0.4	0.4
Wetlands Remaining Wetlands	+	+	+	+	+	+
International Bunker Fuels[b]	*1.1*	*0.9*	*0.9*	*1.0*	*1.0*	*1.0*
HFCs	**36.9**	**61.8**	**100.1**	**116.1**	**119.1**	**125.5**
Substitution of Ozone Depleting Substances[c]	0.3	28.5	71.2	100.0	105.0	108.3
HCFC-22 Production	36.4	33.0	28.6	15.8	13.8	17.0
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.3	0.3
PFCs	**20.8**	**15.6**	**13.5**	**6.2**	**6.0**	**7.5**
Aluminum Production	18.5	11.8	8.6	3.0	2.5	3.8
Semiconductor Manufacture	2.2	3.8	4.9	3.2	3.5	3.6
SF_6	**32.8**	**28.1**	**19.2**	**17.9**	**17.0**	**16.5**
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.0
Semiconductor Manufacture	0.5	0.9	1.1	1.0	1.0	0.8
Total	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Parentheses indicate negative values or sequestration.

[b] Emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption are not included in totals.

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

Note: Totals may not sum due to independent rounding.

Emissions of all gases can be summed from each source category from Intergovernmental Panel on Climate Change (IPCC) guidance (see Table 2-3 and Figure 2-4). Over the eighteen-year period of 1990 to 2007, total emissions in the Energy, Industrial Processes, and Agriculture sectors grew by 976.7 Tg CO_2 Eq. (19 percent), 28.5 Tg CO_2 Eq. (9 percent), and 28.9 Tg CO_2 Eq. (8 percent), respectively. Emissions decreased in the Waste and Solvent and Other Product Use sectors by 11.5 Tg CO_2 Eq. (6 percent) and less than 0.1 Tg CO_2 Eq. (less than 0.4 percent), respectively. Over the same period, estimates of net C sequestration in the Land Use, Land-Use Change, and Forestry sector increased by 192.5 Tg CO_2 Eq. (23 percent).

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

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**5,076,694**	**5,407,885**	**5,955,177**	**6,090,838**	**6,014,871**	**6,103,408**
Fossil Fuel Combustion	4,708,918	5,013,910	5,561,515	5,723,477	5,635,418	5,735,789
Electricity Generation	1,809,685	1,938,862	2,283,177	2,381,002	2,327,313	2,397,191
Transportation	1,484,485	1,598,668	1,800,305	1,881,470	1,880,874	1,887,403
Industrial	834,204	862,557	844,554	828,008	844,505	845,416
Residential	337,715	354,443	370,352	358,036	321,852	340,625
Commercial	214,544	224,400	226,932	221,761	206,049	214,351
U.S. Territories	28,285	34,978	36,195	53,201	54,824	50,803
Non-Energy Use of Fuels	116,977	137,460	144,473	138,070	145,137	133,910
Iron and Steel Production & Metallurgical Coke Production	109,760	103,116	95,062	73,190	76,100	77,370
Cement Production	33,278	36,847	41,190	45,910	46,562	44,525
Natural Gas Systems	33,733	33,810	29,394	29,463	29,540	28,680
Incineration of Waste	10,950	15,712	17,485	19,532	19,824	20,786
Lime Production	11,533	13,325	14,088	14,379	15,100	14,595
Ammonia Production and Urea Consumption	16,831	17,796	16,402	12,849	12,300	13,786
Cropland Remaining Cropland	7,084	7,049	7,541	7,854	7,889	8,007
Limestone and Dolomite Use	5,127	6,651	5,056	6,768	8,035	6,182
Aluminum Production	6,831	5,659	6,086	4,142	3,801	4,251
Soda Ash Production and Consumption	4,141	4,304	4,181	4,228	4,162	4,140
Petrochemical Production	2,221	2,750	3,004	2,804	2,573	2,636
Titanium Dioxide Production	1,195	1,526	1,752	1,755	1,876	1,876
Carbon Dioxide Consumption	1,416	1,422	1,421	1,321	1,709	1,867
Ferroalloy Production	2,152	2,036	1,893	1,392	1,505	1,552
Phosphoric Acid Production	1,529	1,513	1,382	1,386	1,167	1,166
Wetlands Remaining Wetlands	1,033	1,018	1,227	1,079	879	1,010
Zinc Production	949	1,013	1,140	465	529	530
Petroleum Systems	376	341	325	287	288	287
Lead Production	285	298	311	266	270	267
Silicon Carbide Production and Consumption	375	329	248	219	207	196
Land Use, Land-Use Change, and Forestry (Sink)[a]	*(841,430)*	*(850,952)*	*(717,506)*	*(1,122,745)*	*(1,050,541)*	*(1,062,566)*
Biomass—Wood[b]	*215,186*	*229,091*	*218,088*	*208,927*	*209,926*	*209,785*
International Bunker Fuels[b]	*114,330*	*101,620*	*98,966*	*111,487*	*110,520*	*108,756*
Biomass—Ethanol[b]	*4,155*	*7,683*	*9,188*	*22,554*	*30,459*	*38,044*
CH_4	**29,360**	**29,325**	**28,148**	**26,748**	**27,713**	**27,872**
Enteric Fermentation	6,342	6,837	6,398	6,474	6,580	6,618
Landfills	7,105	6,871	5,825	6,088	6,211	6,327
Natural Gas Systems	6,171	6,314	6,231	5,062	4,991	4,985
Coal Mining	4,003	3,193	2,881	2,719	2,780	2,744
Manure Management	1,447	1,642	1,804	1,991	1,993	2,093
Forest Land Remaining Forest Land	218	293	983	676	1,489	1,381
Petroleum Systems	1,613	1,524	1,441	1,346	1,346	1,370
Wastewater Treatment	1,120	1,183	1,200	1,159	1,165	1,160
Stationary Combustion	352	340	315	318	300	315

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

Gas/Source	1990	1995	2000	2005	2006	2007
Rice Cultivation	339	363	357	326	282	293
Abandoned Underground Coal Mines	288	392	350	265	263	273
Mobile Combustion	225	207	163	121	115	109
Composting	15	35	60	75	75	79
Petrochemical Production	41	52	59	51	48	48
Field Burning of Agricultural Residues	33	32	38	41	39	42
Iron and Steel Production & Metallurgical Coke Production	46	47	44	34	35	33
Ferroalloy Production	1	1	1	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+
International Bunker Fuels[b]	*8*	*6*	*6*	*7*	*7*	*7*
N_2O	**1,016**	**1,078**	**1,062**	**1,019**	**1,007**	**1,006**
Agricultural Soil Management	646	653	660	679	672	671
Mobile Combustion	141	173	170	118	108	97
Nitric Acid Production	64	72	71	60	59	70
Manure Management	39	42	45	46	47	47
Stationary Combustion	41	43	47	48	47	47
Adipic Acid Production	49	56	20	19	19	19
Wastewater Treatment	12	13	14	15	15	16
N_2O from Product Uses	14	15	16	14	14	14
Forest Land Remaining Forest Land	2	2	8	6	11	11
Composting	1	3	4	6	6	6
Settlements Remaining Settlements	3	4	4	5	5	5
Field Burning of Agricultural Residues	1	1	1	2	2	2
Incineration of Waste	2	1	1	1	1	1
Wetlands Remaining Wetlands	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*3*	*3*	*3*	*3*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[c]	M	M	M	M	M	M
HCFC-22 Production	3	3	2	1	1	1
Semiconductor Manufacture	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**
Aluminum Production	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	1	1	1	1	1	1
Magnesium Production and Processing	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+

\+ Does not exceed 0.5 Gg.

M Mixture of multiple gases

[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total. Parentheses indicate negative values or sequestration.

[b] Emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption are not included in totals.

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

Note: Totals may not sum due to independent rounding.

Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector (Tg CO_2 Eq.)

Chapter/IPCC Sector	1990	1995	2000	2005	2006	2007
Energy	5,193.6	5,520.1	6,059.9	6,169.2	6,084.4	6,170.3
Industrial Processes	325.2	345.8	356.3	337.6	343.9	353.8
Solvent and Other Product Use	4.4	4.6	4.9	4.4	4.4	4.4
Agriculture	384.2	402.0	399.4	410.8	410.3	413.1
Land Use, Land-Use Change, and Forestry (Emissions)	14.2	16.2	33.0	26.4	45.1	42.9
Waste	177.1	174.7	154.6	160.2	163.0	165.6
Total Emissions	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**
Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Sinks)[a]	(841.4)	(851.0)	(717.5)	(1,122.7)	(1,050.5)	(1,062.6)
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**

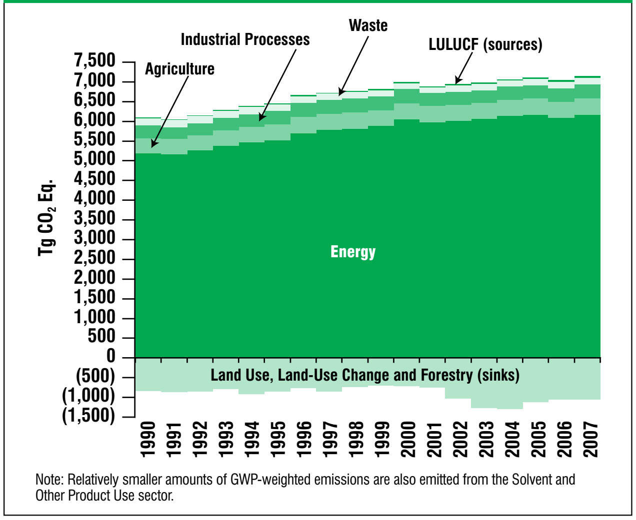
[a] The net CO_2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Sinks are only included in net emissions total.

Note: Totals may not sum due to independent rounding.

Note: Parentheses indicate negative values or sequestration.

Figure 2-4

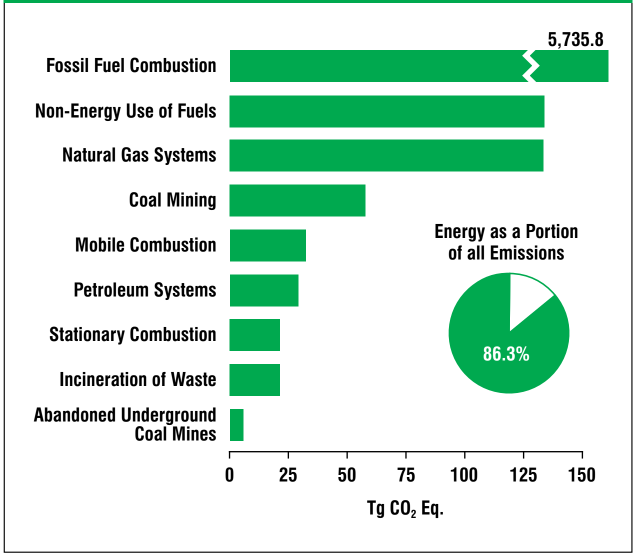
U.S. Greenhouse Gas Emissions and Sinks by Chapter/IPCC Sector



Note: Relatively smaller amounts of GWP-weighted emissions are also emitted from the Solvent and Other Product Use sector.

Figure 2-5

2007 Energy Chapter Greenhouse Gas Sources



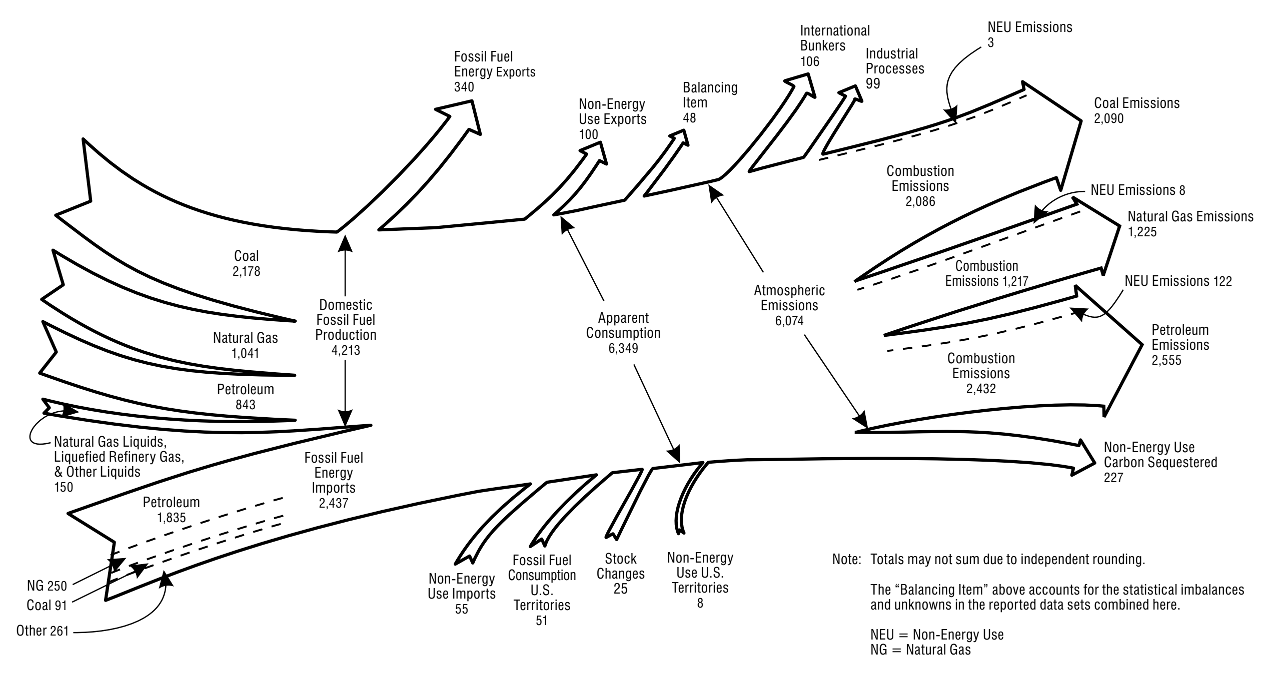
Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2007. In 2007, approximately 85 percent of the energy consumed in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 15 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 CO_2 as well as other greenhouse gas emissions from energy consumption is presented in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (35 percent and 14 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.

CO_2 emissions from fossil fuel combustion are presented in Table 2-5 based on the underlying U.S. energy consumer data collected by EIA. Estimates of CO_2 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

Figure 2-6

2007 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

The "Balancing Item" above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

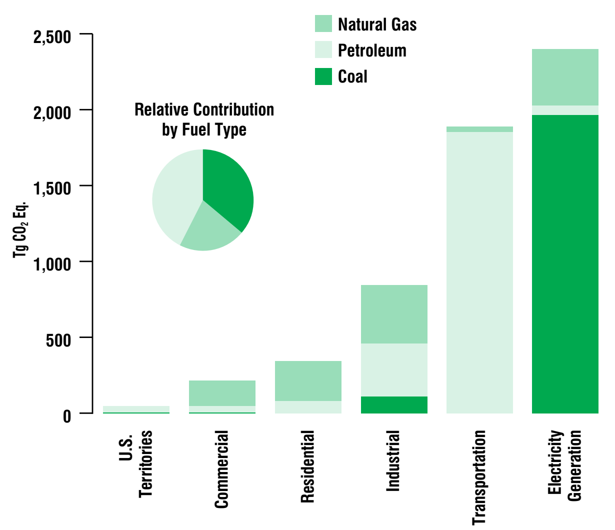
NEU = Non-Energy Use
NG = Natural Gas

power sector comprises electricity-only and combined-heat-and-power (CHP) plants within the 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 consists of living quarters for private households. EIA's fuel consumption data for the commercial sector consists 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, Figure 2-7, and Figure 2-8 summarize CO_2 emissions from fossil fuel combustion by end-use sector.

The main driver of emissions in the energy sector is CO_2 from fossil fuel combustion. The transportation end-

Figure 2-7

2007 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

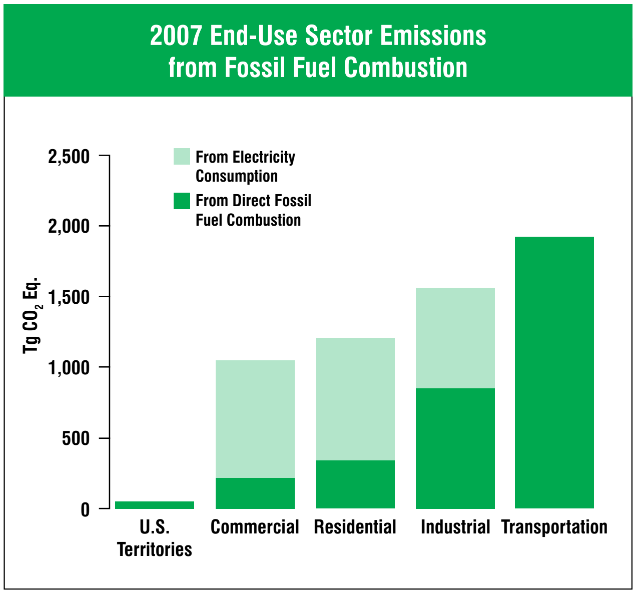
Table 2-4: Emissions from Energy (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**4,871.0**	**5,201.2**	**5,753.2**	**5,910.8**	**5,830.2**	**5,919.5**
Fossil Fuel Combustion	4,708.9	5,013.9	5,561.5	5,723.5	5,635.4	5,735.8
Electricity Generation	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
Transportation	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Industrial	834.2	862.6	844.6	828.0	844.5	845.4
Residential	337.7	354.4	370.4	358.0	321.9	340.6
Commercial	214.5	224.4	226.9	221.8	206.0	214.4
U.S. Territories	28.3	35.0	36.2	53.2	54.8	50.8
Non-Energy Use of Fuels	117.0	137.5	144.5	138.1	145.1	133.9
Natural Gas Systems	33.7	33.8	29.4	29.5	29.5	28.7
Incineration of Waste	10.9	15.7	17.5	19.5	19.8	20.8
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3
Wood Biomass and Ethanol Consumption[a]	*219.3*	*236.8*	*227.3*	*231.5*	*240.4*	*247.8*
International Bunker Fuels[a]	*114.3*	*101.6*	*99.0*	*111.5*	*110.5*	*108.8*
CH_4	**265.7**	**251.4**	**239.0**	**206.5**	**205.7**	**205.7**
Natural Gas Systems	129.6	132.6	130.8	106.3	104.8	104.7
Coal Mining	84.1	67.1	60.5	57.1	58.4	57.6
Petroleum Systems	33.9	32.0	30.3	28.3	28.3	28.8
Stationary Combustion	7.4	7.1	6.6	6.7	6.3	6.6
Abandoned Underground Coal Mines	6.0	8.2	7.4	5.6	5.5	5.7
Mobile Combustion	4.7	4.3	3.4	2.5	2.4	2.3
International Bunker Fuels[a]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**57.0**	**67.5**	**67.7**	**51.9**	**48.5**	**45.2**
Mobile Combustion	43.7	53.7	52.8	36.7	33.5	30.1
Stationary Combustion	12.8	13.3	14.5	14.8	14.5	14.7
Incineration of Waste	0.5	0.5	0.4	0.4	0.4	0.4
International Bunker Fuels[a]	*1.1*	*0.9*	*0.9*	*1.0*	*1.0*	*1.0*
Total	**5,193.6**	**5,520.1**	**6,059.9**	**6,169.2**	**6,084.4**	**6,170.3**

[a] These values are presented for informational purposes only and are not included in totals or are already accounted for in other source categories.
Note: Totals may not sum due to independent rounding.

use sector accounted for 1,892.2 Tg CO_2 Eq. in 2007, or approximately 33 percent of total CO_2 emissions from fossil fuel combustion, the largest share of any end-use economic sector.[3] The industrial end-use sector accounted for 27 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial end-use sectors accounted for an average 21 and 18 percent, respectively, of CO_2 emissions from fossil fuel combustion. Both end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity consumption for lighting, heating, air conditioning, and operating appliances contributing to about 72 and 79 percent of emissions from the residential and commercial end-use sectors, respectively. Significant trends in emissions from

Figure 2-8


2007 End-Use Sector Emissions from Fossil Fuel Combustion

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[3] Note that electricity generation is the largest emitter of CO_2 when electricity is not distributed among end-use sectors.

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

End-Use Sector	1990	1995	2000	2005	2006	2007
Transportation	**1,487.5**	**1,601.7**	**1,803.7**	**1,886.2**	**1,885.4**	**1,892.2**
Combustion	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Electricity	3.0	3.0	3.4	4.7	4.5	4.8
Industrial	**1,516.8**	**1,575.5**	**1,629.6**	**1,558.5**	**1,550.7**	**1,553.4**
Combustion	834.2	862.6	844.6	828.0	844.5	845.4
Electricity	682.6	712.9	785.0	730.5	706.2	708.0
Residential	**927.1**	**993.3**	**1,128.2**	**1,207.2**	**1,145.9**	**1,198.0**
Combustion	337.7	354.4	370.4	358.0	321.9	340.6
Electricity	589.4	638.8	757.9	849.2	824.1	857.4
Commercial	**749.2**	**808.5**	**963.8**	**1,018.4**	**998.6**	**1,041.4**
Combustion	214.5	224.4	226.9	221.8	206.0	214.4
Electricity	534.7	584.1	736.8	796.6	792.5	827.1
U.S. Territories	**28.3**	**35.0**	**36.2**	**53.2**	**54.8**	**50.8**
Total	**4,708.9**	**5,013.9**	**5,561.5**	**5,723.5**	**5,635.4**	**5,735.8**
Electricity Generation	**1,809.7**	**1,938.9**	**2,283.2**	**2,381.0**	**2,327.3**	**2,397.2**

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

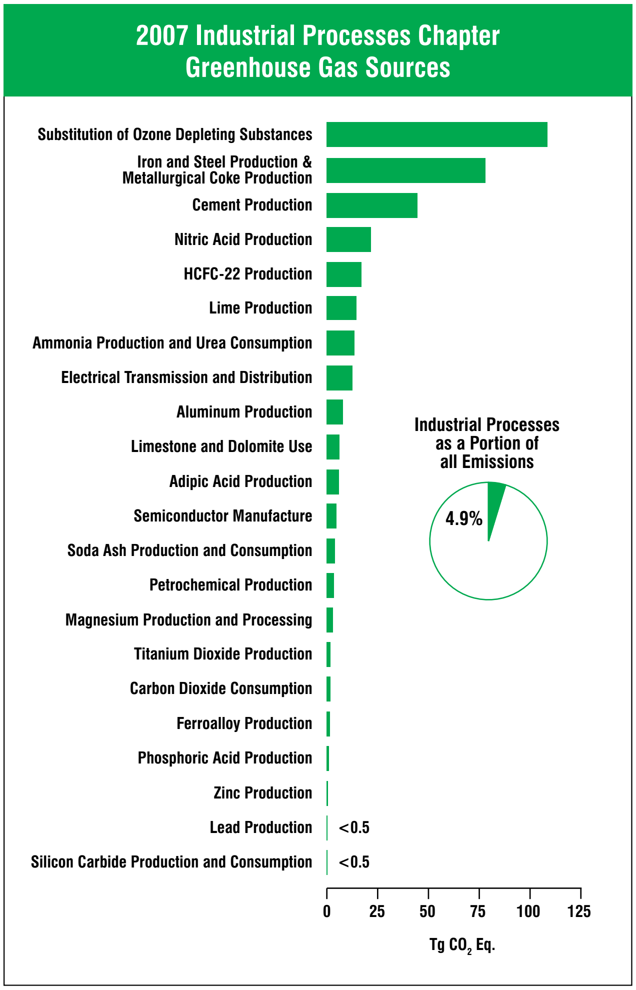
energy source categories over the eighteen-year period from 1990 through 2007 included the following:

- Total CO_2 emissions from fossil fuel combustion increased from 4,708.9 Tg CO_2 Eq. to 5,735.8 Tg CO_2 Eq.—a 22 percent total increase over the eighteen-year period. From 2006 to 2007, these emissions increased by 100.4 Tg CO_2 Eq. (1.8 percent).
- CO_2 emissions from non-energy use of fossil fuels have increased 16.9 Tg CO_2 Eq. (14.5 percent) from 1990 through 2007. Emissions from non-energy uses of fossil fuels were 133.9 Tg CO_2 Eq. in 2007, which constituted 2.2 percent of total national CO_2 emissions.
- CH_4 emissions from natural gas systems were 104.7 Tg CO_2 Eq. in 2007; emissions have declined by 24.9 Tg CO_2 Eq. (19 percent) since 1990. This decline has been due to improvements in technology and management practices, as well as some replacement of old equipment.
- CH_4 emissions from coal mining were 57.6 Tg CO_2 Eq. This decline of 26.4 Tg CO_2 Eq. (31 percent) from 1990 results from the mining of less gassy coal from underground mines and the increased use of CH_4 collected from degasification systems.
- In 2007, N_2O emissions from mobile combustion were 30.1 Tg CO_2 Eq. (approximately 10 percent of U.S. N_2O emissions). From 1990 to 2007, N_2O emissions from mobile combustion decreased by 31 percent. However, from 1990 to 1998 emissions increased by 26 percent, due to control technologies that reduced NO_x emissions while increasing N_2O emissions. Since 1998, newer control technologies have led to a steady decline in N_2O from this source.
- CO_2 emissions from incineration of waste (20.8 Tg CO_2 Eq. in 2007) increased by 9.8 Tg CO_2 Eq. (90 percent) from 1990 through 2007, as the volume of plastics and other fossil carbon-containing materials in municipal solid waste grew.

Industrial Processes

Emissions are produced as a byproduct of many non-energy-related industrial process activities. For example, industrial processes can chemically transform raw materials, which often release waste gases such as CO_2, CH_4, and N_2O. These processes include iron and steel production and metallurgical coke production, cement production, ammonia production and urea application, lime manufacture, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash manufacture and use, titanium dioxide production, phosphoric acid production, ferroalloy production, CO_2 consumption, silicon carbide production and consumption, aluminum production, petrochemical production, nitric acid production, adipic acid production, lead production, and zinc production (see Figure 2-9).

Figure 2-9



2007 Industrial Processes Chapter Greenhouse Gas Sources

Additionally, emissions from industrial processes release HFCs, PFCs and SF_6. Table 2-6 presents greenhouse gas emissions from industrial processes by source category.

Overall, emissions from industrial processes increased by 8.8 percent from 1990 to 2007 despite decreases in emissions from several industrial processes, such as iron and steel production and metallurgical coke production, aluminum production, HCFC-22 production, and electrical transmission and distribution. The increase in overall emissions was driven by a rise in the emissions originating from cement manufacture and, primarily, the emissions from the use of substitutes for ozone depleting substances. Significant trends in emissions from industrial processes source categories over the eighteen-year period from 1990 through 2007 included the following:

- HFC emissions from ODS substitutes have been increasing from small amounts in 1990 to 108.3 Tg CO_2 Eq. in 2007. This increase results from 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 accelerate over the next decade as HCFCs—which are interim substitutes in many applications—are phased out under the provisions of the Copenhagen Amendments to the Montreal Protocol.
- Carbon dioxide and CH_4 emissions from iron and steel production and metallurgical coke production increased by 1.6 percent to 78.1 Tg CO_2 Eq. in 2007, but have declined overall by 32.6 Tg CO_2 Eq. (29.5 percent) from 1990 through 2007, due to restructuring of the industry, technological improvements, and increased scrap utilization.
- PFC emissions from aluminum production decreased by 79 percent (14.7 Tg CO_2 Eq.) from 1990 to 2007, due to both industry emission reduction efforts and lower domestic aluminum production.
- Nitrous oxide emissions from adipic acid production were 5.9 Tg CO_2 Eq. in 2007, and have decreased significantly in recent years from the widespread installation of pollution control measures. Emissions from adipic acid production have decreased 61 percent since 1990, and emissions from adipic acid production have fluctuated by less than 1.2 Tg CO_2 Eq. annually since 1998.
- Carbon dioxide emissions from ammonia production and urea application (13.8 Tg CO_2 Eq. in 2007) have decreased by 3.0 Tg CO_2 Eq. (18 percent) since 1990, due to a decrease in domestic ammonia production. This decrease in ammonia production can be attributed to market fluctuations and high natural gas prices.

Solvent and Other Product Use

Greenhouse gas emissions are produced as a byproduct of various solvent and other product uses. In the United States, N_2O Emissions from Product Uses, the only source of greenhouse gas emissions from this sector, accounted for 4.4 Tg CO_2 Eq., or less than 0.1 percent of total U.S. emissions in 2007 (see Table 2-7).

In 2007, N_2O emissions from product uses constituted 1 percent of U.S. N_2O emissions. From 1990 to 2007, emissions from this source category decreased by less than 0.5 percent, though slight increases occurred in intermediate years.

Table 2-6: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**197.6**	**198.6**	**193.2**	**171.1**	**175.9**	**174.9**
Iron and Steel Production & Metallurgical Coke Production	109.8	103.1	95.1	73.2	76.1	77.4
Cement Manufacture	33.3	36.8	41.2	45.9	46.6	44.5
Lime Manufacture	11.5	13.3	14.1	14.4	15.1	14.6
Ammonia Production & Urea Application	16.8	17.8	16.4	12.8	12.3	13.8
Limestone and Dolomite Use	5.1	6.7	5.1	6.8	8.0	6.2
Aluminum Production	6.8	5.7	6.1	4.1	3.8	4.3
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.2	4.2	4.1
Petrochemical Production	2.2	2.8	3.0	2.8	2.6	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.8	1.9	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	1.3	1.7	1.9
Ferroalloy Production	2.2	2.0	1.9	1.4	1.5	1.6
Phosphoric Acid Production	1.5	1.5	1.4	1.4	1.2	1.2
Zinc Production	0.9	1.0	1.1	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2
CH_4	**1.9**	**2.1**	**2.2**	**1.8**	**1.7**	**1.7**
Petrochemical Production	0.9	1.1	1.2	1.1	1.0	1.0
Iron and Steel Production & Metallurgical Coke Production	1.0	1.0	0.9	0.7	0.7	0.7
Ferroalloy Production	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+
N_2O	**35.3**	**39.6**	**28.1**	**24.6**	**24.2**	**27.6**
Nitric Acid Production	20.0	22.3	21.9	18.6	18.2	21.7
Adipic Acid Production	15.3	17.3	6.2	5.9	5.9	5.9
HFCs	**36.9**	**61.8**	**100.1**	**116.1**	**119.1**	**125.5**
Substitution of Ozone Depleting Substances[a]	0.3	28.5	71.2	100.0	105.0	108.3
HCFC-22 Production	36.4	33.0	28.6	15.8	13.8	17.0
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.3	0.3
PFCs	**20.8**	**15.6**	**13.5**	**6.2**	**6.0**	**7.5**
Aluminum Production	18.5	11.8	8.6	3.0	2.5	3.8
Semiconductor Manufacture	2.2	3.8	4.9	3.2	3.5	3.6
SF_6	**32.8**	**28.1**	**19.2**	**17.9**	**17.0**	**16.5**
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.0
Semiconductor Manufacture	0.5	0.9	1.1	1.0	1.0	0.8
Total	**325.2**	**345.8**	**356.3**	**337.6**	**343.9**	**353.8**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

Note: Totals may not sum due to independent rounding.

Table 2-7: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq.)

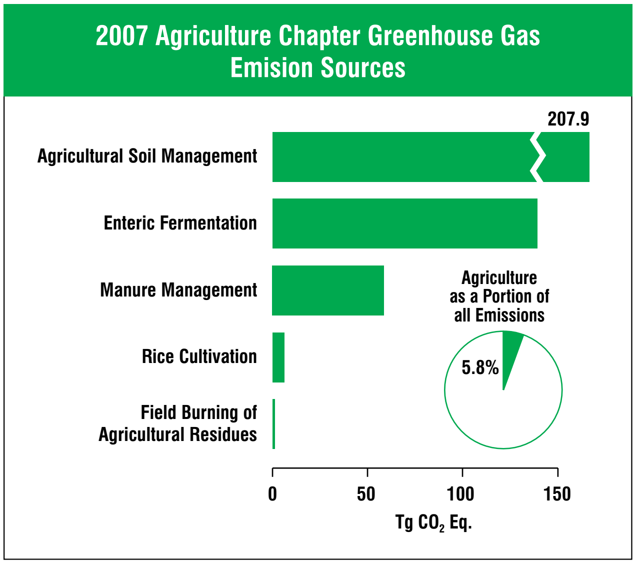
Gas/Source	1990	1995	2000	2005	2006	2007
N_2O	**4.4**	**4.6**	**4.9**	**4.4**	**4.4**	**4.4**
N_2O from Product Uses	4.4	4.6	4.9	4.4	4.4	4.4
Total	**4.4**	**4.6**	**4.9**	**4.4**	**4.4**	**4.4**

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 (see Figure 2-10).

In 2007, agricultural activities were responsible for emissions of 413.1 Tg CO_2 Eq., or 5.8 percent of total U.S. greenhouse gas emissions (see Table 2-8). Methane and N_2O were the primary greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented about 24 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2007. Agricultural soil management activities, such as fertilizer application and other cropping practices, were the largest source of U.S. N_2O emissions in 2007, accounting for 67 percent.

Figure 2-10


2007 Agriculture Chapter Greenhouse Gas Emision Sources

Some significant trends in U.S. emissions from agriculture include the following:

- Agricultural soils produced approximately 67 percent of N_2O emissions in the United States in 2007. Estimated emissions from this source in 2007 were 207.9 Tg CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2007, although overall emissions were 3.8 percent higher in 2007 than in 1990. N_2O emissions from this source have not shown any significant long-term trend, as they are highly sensitive to the amount of N applied to soils, which has not changed significantly over the time-period, and to weather patterns and crop type.
- Enteric fermentation was the largest source of CH_4 emissions in 2007, at 139.0 Tg CO_2 Eq. Although emissions from enteric fermentation have increased by 4 percent between 1990 and 2007, emissions increased about 8 percent between 1990 and 1995 and decreased about 7 percent from 1995 to 2004, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. The last three years have shown an increase in emissions. During this timeframe, populations of sheep have decreased 46 percent since 1990 while horse populations have increased over 80 percent, mostly over the last 6 years. Goat and swine populations have increased 1 percent and 21 percent, respectively, during this timeframe.
- Overall, emissions from manure management increased 38 percent between 1990 and 2007. This encompassed

Table 2-8: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**171.4**	**186.3**	**180.5**	**185.5**	**186.8**	**190.0**
Enteric Fermentation	133.2	143.6	134.4	136.0	138.2	139.0
Manure Management	30.4	34.5	37.9	41.8	41.9	44.0
Rice Cultivation	7.1	7.6	7.5	6.8	5.9	6.2
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.9	0.8	0.9
N_2O	**212.8**	**215.6**	**218.9**	**225.3**	**223.5**	**223.1**
Agricultural Soil Management	200.3	202.3	204.5	210.6	208.4	207.9
Manure Management	12.1	12.9	14.0	14.2	14.6	14.7
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.5	0.5
Total	**384.2**	**402.0**	**399.4**	**410.8**	**410.3**	**413.1**

Note: Totals may not sum due to independent rounding.

an increase of 45 percent for CH_4, from 30.4 Tg CO_2 Eq. in 1990 to 44.0 Tg CO_2 Eq. in 2007; and an increase of 22 percent for N_2O, from 12.1 Tg CO_2 Eq. in 1990 to 14.7 Tg CO_2 Eq. in 2007. 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 CH_4 emissions.

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 carbon 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 an uptake (sequestration) of carbon in the United States, which offset about 14.9 percent of total U.S. greenhouse gas emissions in 2007. Forests (including vegetation, soils, and harvested wood) accounted for approximately 86 percent of total 2007 net CO_2 flux, urban trees accounted for 9 percent, mineral and organic soil carbon stock changes accounted for 4 percent, and landfilled yard trimmings and food scraps accounted for 1 percent of the total net flux in 2007. 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 70 percent more C than is emitted from these soils through liming, urea fertilization, or both. The mineral soil C sequestration is largely due to the conversion of cropland to hay production fields, the limited use of bare-summer fallow areas in semi-arid areas, and an increase in the adoption of conservation tillage practices. 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.

Land use, land-use change, and forestry activities in 2007 resulted in a net C sequestration of 1,062.6 Tg CO_2 Eq. (Table 2-9). This represents an offset of approximately 17.4 percent of total U.S. CO_2 emissions, or 14.9 percent of total greenhouse gas emissions in 2007. Between 1990 and 2007, total land use, land-use change, and forestry net C flux resulted in a 26.3 percent increase in CO_2 sequestration.

Land use, land-use change, and forestry source categories also resulted in emissions of CO_2, CH_4, and N_2O that are not included in the net flux estimates presented in Table 2-10. The application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization resulted in CO_2 emissions of 8.0 Tg CO_2 Eq. in 2007, an increase of 13 percent relative to 1990. Lands undergoing peat extraction resulted in CO_2 emissions of 1.0 Tg CO_2 Eq. (1,010 Gg), and N_2O emissions of less than 0.01 Tg CO_2 Eq. N_2O emissions from the application of synthetic fertilizers to forest soils have increased from 1990 to 0.3 Tg CO_2 Eq. in 2007. Settlement soils in 2007 resulted in direct N_2O emissions of 1.6 Tg CO_2 Eq., a 61 percent increase relative to 1990. Non-CO_2 emissions from forest fires in 2007 resulted in CH_4 emissions of 29 Tg CO_2 Eq., and in N_2O emissions of 2.9 Tg CO_2 Eq.

Other significant trends from 1990 to 2007 in land use, land-use change, and forestry emissions include:

- Net C sequestration by forest land has increased 38 percent. This is primarily due to increased forest

Table 2-9: Net CO_2 Flux from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	2000	2005	2006	2007
Forest Land Remaining Forest Land	(661.1)	(686.6)	(512.6)	(975.7)	(900.3)	(910.1)
Cropland Remaining Cropland	(29.4)	(22.9)	(30.2)	(18.3)	(19.1)	(19.7)
Land Converted to Cropland	2.2	2.9	2.4	5.9	5.9	5.9
Grassland Remaining Grassland	(46.7)	(36.4)	(51.4)	(4.6)	(4.6)	(4.7)
Land Converted to Grassland	(22.3)	(22.5)	(32.0)	(26.7)	(26.7)	(26.7)
Settlements Remaining Settlements	(60.6)	(71.5)	(82.4)	(93.3)	(95.5)	(97.6)
Other (Landfilled Yard Trimmings and Food Scraps)	(23.5)	(13.9)	(11.3)	(10.2)	(10.4)	(9.8)
Total	**(841.4)**	**(851.0)**	**(717.5)**	**(1,122.7)**	**(1,050.5)**	**(1,062.6)**

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

Table 2-10: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**8.1**	**8.1**	**8.8**	**8.9**	**8.8**	**9.0**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.4	4.3	4.3	4.2	4.1
Cropland Remaining Cropland: Urea Fertilization	2.4	2.7	3.2	3.5	3.7	4.0
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.0	1.2	1.1	0.9	1.0
CH_4	**4.6**	**6.1**	**20.6**	**14.2**	**31.3**	**29.0**
Forest Land Remaining Forest Land: Forest Fires	4.6	6.1	20.6	14.2	31.3	29.0
N_2O	**1.5**	**2.0**	**3.6**	**3.3**	**5.0**	**4.9**
Forest Land Remaining Forest Land: Forest Fires	0.5	0.6	2.1	1.4	3.2	2.9
Forest Land Remaining Forest Land: Forest Soils	0.0	0.1	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils	1.0	1.2	1.2	1.5	1.5	1.6
Total	**14.2**	**16.2**	**33.0**	**26.4**	**45.1**	**42.9**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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 18 years, although only at an average rate of 0.25 percent per year.

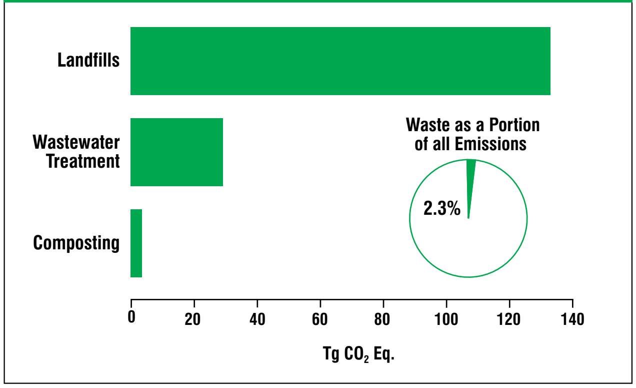
- Net sequestration of C by urban trees has increased by 61 percent over the period from 1990 to 2007. This is primarily due to an increase in urbanized land area in the United States.
- Annual C sequestration in landfilled yard trimmings and food scraps has decreased by 58 percent since 1990. This is due in part to a decrease in the amount of yard trimmings and food scraps generated. In addition, the proportion of yard trimmings and food scraps landfilled has decreased, as there has been a significant rise in the number of municipal composting facilities in the United States.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11). In 2007, landfills were the second largest source of anthropogenic CH_4 emissions, accounting for 23 percent of total U.S. CH_4 emissions.[4] Additionally, wastewater treatment accounts for 4 percent of U.S. CH_4 emissions, and 2 percent of N_2O

Figure 2-11

2007 Waste Chapter Greenhouse Gas Emission Sources



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[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.

Table 2-11: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**173.0**	**169.9**	**148.8**	**153.8**	**156.5**	**158.9**
Landfills	149.2	144.3	122.3	127.8	130.4	132.9
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4
Composting	0.3	0.7	1.3	1.6	1.6	1.7
N_2O	**4.0**	**4.8**	**5.8**	**6.5**	**6.6**	**6.7**
Wastewater Treatment	3.7	4.0	4.5	4.8	4.8	4.9
Composting	0.4	0.8	1.4	1.7	1.8	1.8
Total	177.1	174.7	154.6	160.2	163.0	165.6

Note: Totals may not sum due to independent rounding.

emissions. Emissions of CH_4 and N_2O from composting grew from 1990 to 2007, and resulted in emissions of 3.5 Tg CO_2 Eq. in 2007. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 2-11.

Overall, in 2007, waste activities generated emissions of 165.6 Tg CO_2 Eq., or 2.3 percent of total U.S. greenhouse gas emissions.

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

- From 1990 to 2007, net CH_4 emissions from landfills decreased by 16.3 Tg CO_2 Eq. (11 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,[5] which has more than offset the additional CH_4 emissions resulting from an increase in the amount of municipal solid waste landfilled.
- From 1990 to 2007, CH_4 and N_2O emissions from wastewater treatment increased by 0.8 Tg CO_2 Eq. (4 percent) and 1.2 Tg CO_2 Eq. (32 percent), respectively.
- Methane and N_2O emissions from composting each increased by less than 0.1 Tg CO_2 Eq. (4 percent) from 2006 to 2007. Emissions from composting have been continually increasing since 1990, from 0.7 Tg CO_2 Eq. to 3.5 Tg CO_2 Eq. in 2007, a four-fold increase over the time series.

2.2. Emissions by Economic Sector

Throughout this report, emission estimates are grouped into six sectors (i.e., chapters) defined by the IPCC and detailed above: Energy; Industrial Processes; Solvent and Other Product Use; Agriculture; Land Use, Land-Use Change, and Forestry; 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 (34 percent) of U.S. greenhouse gas emissions in 2007. Transportation activities, in aggregate, accounted for the second largest portion (28 percent). Emissions from industry accounted for about 20 percent of U.S. greenhouse gas emissions in 2007. 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 18 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 5 percent, and primarily consisted of CO_2 emissions from fossil fuel combustion. Activities related to agriculture accounted for roughly 7 percent of U.S. emissions;

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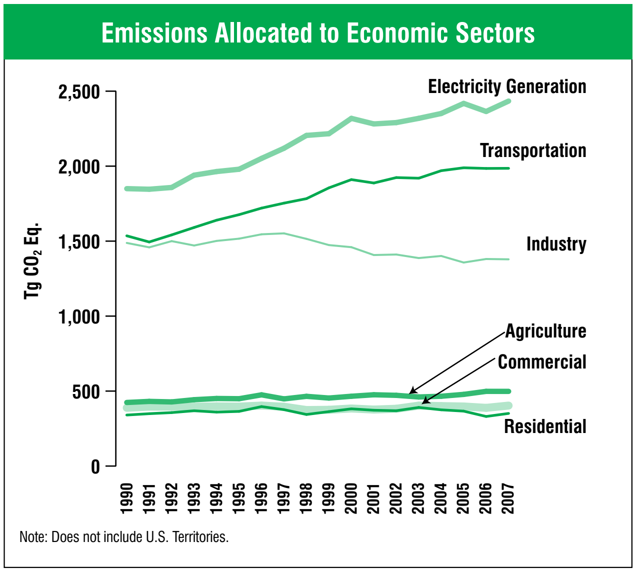
[5] The CO_2 produced from combusted landfill CH_4 at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. The commercial sector accounted for roughly 6 percent of emissions, while U.S. territories accounted for about 1 percent.

Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, and landfilling of yard trimmings.

Table 2-12 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 2007.

Figure 2-12



Emissions Allocated to Economic Sectors

Note: Does not include U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2007)

Sector/Source	1990	1995	2000	2005	2006	2007	Percent[a]
Electric Power Industry	**1,859.1**	**1,989.0**	**2,329.3**	**2,429.4**	**2,375.5**	**2,445.1**	**34.2%**
CO_2 from Fossil Fuel Combustion	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2	33.5%
Incineration of Waste	11.4	16.2	17.9	19.9	20.2	21.2	0.3%
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7	0.2%
Stationary Combustion	8.6	9.1	10.6	11.0	10.8	11.0	0.2%
Limestone and Dolomite Use	2.6	3.3	2.5	3.4	4.0	3.1	+
Transportation	**1,543.6**	**1,685.2**	**1,919.7**	**1,998.9**	**1,994.4**	**1,995.2**	**27.9%**
CO_2 from Fossil Fuel Combustion	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4	26.4%
Substitution of Ozone Depleting Substances	+	18.6	52.6	69.7	69.5	67.0	0.9%
Mobile Combustion	47.3	56.6	54.7	37.5	34.1	30.6	0.4%
Non-Energy Use of Fuels	11.9	11.3	12.1	10.2	9.9	10.2	0.1%
Industry	**1,496.0**	**1,524.5**	**1,467.5**	**1,364.9**	**1,388.4**	**1,386.3**	**19.4%**
CO_2 from Fossil Fuel Combustion	803.4	826.3	806.1	781.6	796.0	797.5	11.2%
Natural Gas Systems	163.3	166.4	160.2	135.8	134.3	133.4	1.9%
Non-Energy Use of Fuels	99.4	120.2	121.4	120.8	127.9	117.0	1.6%
Iron and Steel & Metallurgical Coke Production	110.7	104.1	96.0	73.9	76.8	78.1	1.1%
Coal Mining	84.1	67.1	60.5	57.1	58.4	57.6	0.8%
Cement Production	33.3	36.8	41.2	45.9	46.6	44.5	0.6%
Petroleum Systems	34.2	32.3	30.6	28.6	28.6	29.1	0.4%
Nitric Acid Production	20.0	22.3	21.9	18.6	18.2	21.7	0.3%
HCFC-22 Production	36.4	33.0	28.6	15.8	13.8	17.0	0.2%
Lime Production	11.5	13.3	14.1	14.4	15.1	14.6	0.2%
Ammonia Production and Urea Consumption	16.8	17.8	16.4	12.8	12.3	13.8	0.2%
Aluminum Production	25.4	17.5	14.7	7.1	6.3	8.1	0.1%
Substitution of Ozone Depleting Substances	+	1.2	3.1	5.2	5.7	6.1	0.1%
Adipic Acid Production	15.3	17.3	6.2	5.9	5.9	5.9	0.1%

Table 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (continued)
(Tg CO_2 Eq. and Percent of Total in 2007)

Sector/Source	1990	1995	2000	2005	2006	2007	Percent[a]
Abandoned Underground Coal Mines	6.0	8.2	7.4	5.6	5.5	5.7	0.1%
Semiconductor Manufacture	2.9	4.9	6.2	4.4	4.7	4.7	0.1%
Stationary Combustion	4.7	4.9	4.8	4.5	4.6	4.5	0.1%
N_2O from Product Uses	4.4	4.6	4.9	4.4	4.4	4.4	0.1%
Soda Ash Production and Consumption	4.1	4.3	4.2	4.2	4.2	4.1	0.1%
Petrochemical Production	3.1	3.8	4.2	3.9	3.6	3.7	0.1%
Limestone and Dolomite Use	2.6	3.3	2.5	3.4	4.0	3.1	+
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.0	+
Titanium Dioxide Production	1.2	1.5	1.8	1.8	1.9	1.9	+
Carbon Dioxide Consumption	1.4	1.4	1.4	1.3	1.7	1.9	+
Ferroalloy Production	2.2	2.0	1.9	1.4	1.5	1.6	+
Mobile Combustion	0.9	1.0	1.1	1.3	1.3	1.3	+
Phosphoric Acid Production	1.5	1.5	1.4	1.4	1.2	1.2	+
Zinc Production	0.9	1.0	1.1	0.5	0.5	0.5	+
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	+
Silicon Carbide Production and Consumption	0.4	0.3	0.3	0.2	0.2	0.2	+
Agriculture	**428.5**	**453.7**	**470.2**	**482.6**	**502.9**	**502.8**	**7.0%**
N_2O from Agricultural Soil Management	200.3	202.3	204.5	210.6	208.4	207.9	2.9%
Enteric Fermentation	133.2	143.6	134.4	136.0	138.2	139.0	1.9%
Manure Management	42.4	47.4	51.9	56.0	56.4	58.7	0.8%
CO_2 from Fossil Fuel Combustion	30.8	36.3	38.4	46.4	48.6	47.9	0.7%
CH_4 and N_2O from Forest Fires	5.1	6.8	22.7	15.6	34.4	31.9	0.4%
Rice Cultivation	7.1	7.6	7.5	6.8	5.9	6.2	0.1%
Liming of Agricultural Soils	4.7	4.4	4.3	4.3	4.2	4.1	0.1%
Urea Fertilization	2.4	2.7	3.2	3.5	3.7	4.0	0.1%
Field Burning of Agricultural Residues	1.1	1.0	1.3	1.4	1.3	1.4	+
CO_2 and N_2O from Managed Peatlands	1.0	1.0	1.2	1.1	0.9	1.0	+
Mobile Combustion	0.3	0.4	0.4	0.5	0.5	0.5	+
N_2O from Forest Soils	+	0.1	0.3	0.3	0.3	0.3	+
Stationary Combustion	+	+	+	+	+	+	+
Commercial	**392.9**	**401.0**	**388.2**	**401.8**	**392.6**	**407.6**	**5.7%**
CO_2 from Fossil Fuel Combustion	214.5	224.4	226.9	221.8	206.0	214.4	3.0%
Landfills	149.2	144.3	122.3	127.8	130.4	132.9	1.9%
Substitution of Ozone Depleting Substances	+	0.7	5.5	18.5	22.4	26.6	0.4%
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4	0.3%
Human Sewage	3.7	4.0	4.5	4.8	4.8	4.9	0.1%
Composting	0.7	1.5	2.6	3.3	3.3	3.5	+
Stationary Combustion	1.2	1.3	1.2	1.2	1.1	1.2	+
Residential	**344.5**	**368.8**	**386.0**	**370.5**	**334.9**	**355.3**	**5.0%**
CO_2 from Fossil Fuel Combustion	337.7	354.4	370.4	358.0	321.9	340.6	4.8%
Substitution of Ozone Depleting Substances	0.3	8.1	10.1	6.5	7.5	8.6	0.1%

Table 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (Tg CO_2 Eq. and Percent of Total in 2007) (continued)

Sector/Source	1990	1995	2000	2005	2006	2007	Percent[a]
Stationary Combustion	5.5	5.0	4.3	4.5	4.0	4.4	0.1%
Settlement Soil Fertilization	1.0	1.2	1.2	1.5	1.5	1.6	+
U.S. Territories	**34.1**	**41.1**	**47.3**	**60.5**	**62.3**	**57.7**	**0.8%**
CO_2 from Fossil Fuel Combustion	28.3	35.0	36.2	53.2	54.8	50.8	0.7%
Non-Energy Use of Fuels	5.7	6.0	10.9	7.1	7.3	6.7	0.1%
Stationary Combustion	0.1	0.1	0.1	0.2	0.2	0.2	0.0%
Total Emissions	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**	**100.0%**
Sinks	**(841.4)**	**(851.0)**	**(717.5)**	**(1,122.7)**	**(1,050.5)**	**(1,062.6)**	**(14.9)%**
CO_2 Flux from Forests	(661.1)	(686.6)	(512.6)	(975.7)	(900.3)	(910.1)	(12.7)%
Urban Trees	(60.6)	(71.5)	(82.4)	(93.3)	(95.5)	(97.6)	(1.4)%
CO_2 Flux from Agricultural Soil Carbon Stocks	(96.3)	(78.9)	(111.2)	(43.6)	(44.5)	(45.1)	(0.6)%
Landfilled Yard Trimmings and Food Scraps	(23.5)	(13.9)	(11.3)	(10.2)	(10.4)	(9.8)	(0.1)%
Net Emissions (Sources and Sinks)	**5,257.3**	**5,612.3**	**6,290.7**	**5,985.9**	**6,000.6**	**6,087.5**	**85.1%**

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

[a] Percent of total emissions for year 2007.

Note: Includes all emissions of CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. Parentheses indicate negative values or sequestration. Totals may not sum due to independent rounding.

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 34 percent of total U.S. greenhouse gas emissions in 2007. Emissions increased by 28 percent since 1990, as electricity demand grew and fossil fuels remained the dominant energy source for generation. Electricity generation-related emissions increased from 2006 to 2007 by 3 percent, primarily due to increased CO_2 emissions from fossil fuel combustion. The electricity generation sector in the United States is composed of traditional electric utilities as well as other entities, such as power marketers and non-utility power producers. The majority of electricity generated by these entities was through the combustion of coal in boilers to produce high-pressure steam that is passed through a turbine. Table 2-13 provides a detailed summary of emissions from electricity generation-related activities.

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 retail sales of electricity (EIA 2008a and Duffield 2006). These three source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, and SF_6 from Electrical Transmission and Distribution Systems.[6]

When emissions from electricity are distributed among these sectors, industry accounts for the largest share of U.S. greenhouse gas emissions (30 percent), followed closely by emissions from transportation activities, which account for 28 percent of total emissions. Emissions from the residential

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[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.

Table 2-13: Electricity Generation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Fuel Type or Source	1990	1995	2000	2005	2006	2007
CO_2	**1,823.2**	**1,957.9**	**2,303.2**	**2,403.9**	**2,351.2**	**2,421.1**
CO_2 from Fossil Fuel Combustion	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
Coal	*1,531.1*	*1,648.6*	*1,909.5*	*1,958.4*	*1,932.4*	*1,967.6*
Natural Gas	*176.5*	*229.2*	*281.8*	*319.9*	*338.9*	*373.8*
Petroleum	*101.8*	*60.7*	*91.5*	*102.3*	*55.6*	*55.3*
Geothermal	*0.4*	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	10.9	15.7	17.5	19.5	19.8	20.8
Limestone and Dolomite Use	2.6	3.3	2.5	3.4	4.0	3.1
CH_4	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**
Stationary Combustion[a]	0.6	0.6	0.7	0.7	0.7	0.7
N_2O	**8.5**	**9.0**	**10.4**	**10.7**	**10.5**	**10.7**
Stationary Combustion[a]	8.1	8.6	10.0	10.3	10.1	10.3
Incineration of Waste	0.5	0.5	0.4	0.4	0.4	0.4
SF_6	**26.8**	**21.6**	**15.1**	**14.0**	**13.2**	**12.7**
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7
Total	**1,859.1**	**1,989.0**	**2,329.3**	**2,429.4**	**2,375.5**	**2,445.1**

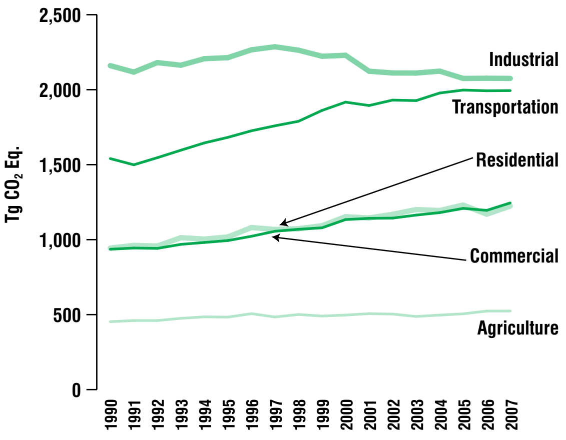
[a] Includes only stationary combustion emissions related to the generation of electricity.
Note: Totals may not sum due to independent rounding.

and commercial sectors also increase substantially when emissions from electricity are included, due to their relatively large share of electricity consumption. In all sectors except agriculture, CO_2 accounts for more than 80 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels.

Table 2-14 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 2007.

Figure 2-13

Emissions with Electricity Distributed to Economic Sectors



Note: Does not include U.S. Territories.

Industry

The industrial end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate. This 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, among others, fugitive CH_4 emissions from coal mining, byproduct CO_2 emissions from cement manufacture, and HFC, PFC, and SF_6 byproduct emissions from semiconductor manufacture. Overall, direct industry sector emissions have declined since 1990, while electricity-related emissions have risen. 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 affect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities

Table 2-14: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2007

Sector/Gas	1990	1995	2000	2005	2006	2007	Percent[a]
Industry	**2,166.5**	**2,219.8**	**2,235.5**	**2,081.2**	**2,082.3**	**2,081.2**	**29.1%**
Direct Emissions	1,496.0	1,524.5	1,467.5	1,364.9	1,388.4	1,386.3	19.4%
CO_2	1,097.9	1,141.7	1,118.3	1,070.1	1,095.8	1,086.4	15.2%
CH_4	291.1	277.8	262.5	230.4	230.2	229.1	3.2%
N_2O	43.6	48.4	37.2	33.1	32.8	36.2	0.5%
HFCs, PFCs, and SF_6	63.3	56.6	49.6	31.3	29.6	34.7	0.5%
Electricity-Related	670.6	695.3	767.9	716.3	693.8	694.9	9.7%
CO_2	657.6	684.4	759.3	708.8	686.7	688.0	9.6%
CH_4	0.2	0.2	0.2	0.2	0.2	0.2	+
N_2O	3.1	3.2	3.4	3.2	3.1	3.0	+
SF_6	9.7	7.5	5.0	4.1	3.9	3.6	0.1%
Transportation	**1,546.7**	**1,688.3**	**1,923.2**	**2,003.6**	**1,999.0**	**2,000.1**	**28.0%**
Direct Emissions	1,543.6	1,685.2	1,919.7	1,998.9	1,994.4	1,995.2	27.9%
CO_2	1,496.3	1,610.0	1,812.4	1,891.7	1,890.8	1,897.6	26.5%
CH_4	4.5	4.1	3.2	2.2	2.1	2.0	+
N_2O	42.7	52.5	51.6	35.2	32.0	28.6	0.4%
HFCs[b]	+	18.6	52.6	69.7	69.5	67.0	0.9%
Electricity-Related	3.1	3.1	3.5	4.8	4.6	4.9	0.1%
CO_2	3.1	3.1	3.5	4.7	4.5	4.8	0.1%
CH_4	+	+	+	+	+	+	+
N_2O	+	+	+	+	+	+	+
SF_6	+	+	+	+	+	+	+
Commercial	**942.2**	**1,000.2**	**1,140.0**	**1,214.6**	**1,201.5**	**1,251.2**	**17.5%**
Direct Emissions	392.9	401.0	388.2	401.8	392.6	407.6	5.7%
CO_2	214.5	224.4	226.9	221.8	206.0	214.4	3.0%
CH_4	173.9	170.8	149.7	154.6	157.3	159.7	2.2%
N_2O	4.4	5.2	6.2	6.8	6.9	7.0	0.1%
HFCs	+	0.7	5.5	18.5	22.4	26.6	0.4%
Electricity-Related	549.3	599.2	751.7	812.8	808.9	843.6	11.8%
CO_2	538.7	589.8	743.3	804.3	800.6	835.3	11.7%
CH_4	0.2	0.2	0.2	0.2	0.2	0.3	+
N_2O	2.5	2.7	3.3	3.6	3.6	3.7	0.1%
SF_6	7.9	6.5	4.9	4.7	4.5	4.4	0.1%
Residential	**950.0**	**1,024.2**	**1,159.2**	**1,237.0**	**1,176.1**	**1,229.8**	**17.2%**
Direct Emissions	344.5	368.8	386.0	370.5	334.9	355.3	5.0%
CO_2	337.7	354.4	370.4	358.0	321.9	340.6	4.8%
CH_4	4.4	4.0	3.4	3.5	3.2	3.5	+
N_2O	2.1	2.2	2.1	2.4	2.4	2.5	+
HFCs	0.3	8.1	10.1	6.5	7.5	8.6	0.1%
Electricity-Related	605.5	655.4	773.2	866.5	841.2	874.5	12.2%
CO_2	593.8	645.1	764.5	857.4	832.5	865.9	12.1%
CH_4	0.2	0.2	0.2	0.3	0.3	0.3	+
N_2O	2.8	3.0	3.4	3.8	3.7	3.8	0.1%
SF_6	8.7	7.1	5.0	5.0	4.7	4.5	0.1%

Table 2-14: U.S Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (Tg CO_2 Eq.) and Percent of Total in 2007 (continued)

Sector/Gas	1990	1995	2000	2005	2006	2007	Percent[a]
Agriculture	**459.2**	**489.7**	**503.2**	**511.7**	**530.0**	**530.1**	**7.4%**
Direct Emissions	428.5	453.7	470.2	482.6	502.9	502.8	7.0%
CO_2	38.9	44.4	47.2	55.3	57.3	56.9	0.8%
CH_4	176.1	192.6	201.3	199.8	218.2	219.2	3.1%
N_2O	213.5	216.7	221.7	227.5	227.4	226.7	3.2%
Electricity-Related	30.6	36.0	33.0	29.0	27.0	27.3	0.4%
CO_2	30.0	35.5	32.6	28.7	26.8	27.0	0.4%
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.2	0.1	0.1	0.1	0.1	+
SF_6	0.4	0.4	0.2	0.2	0.2	0.1	+
U.S. Territories	**34.1**	**41.1**	**47.3**	**60.5**	**62.3**	**57.7**	**0.8%**
Total	**6,098.7**	**6,463.3**	**7,008.2**	**7,108.6**	**7,051.1**	**7,150.1**	**100.0%**

+ Does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
[a] Percent of total emissions for year 2007.
[b] Includes primarily HFC-134a.
Note: Emissions from electricity generation are allocated based on aggregate electricity consumption in each end-use sector.
Totals may not sum due to independent rounding.

accounted for 28 percent of U.S. greenhouse gas emissions in 2007. The largest sources of transportation GHGs in 2007 were passenger cars (33 percent), light duty trucks, which include sport utility vehicles, pickup trucks, and minivans (28 percent), freight trucks (21 percent) and commercial aircraft (8 percent). These figures include direct emissions from fossil fuel combustion, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types. Table 2-15 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals.

From 1990 to 2007, transportation emissions rose by 29 percent due, in large part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 40 percent from 1990 to 2007, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period. A similar set of social and economic trends has led to a significant increase in air travel and freight transportation by both air and road modes during the time series.

Although average fuel economy over this period increased slightly due primarily to the retirement of older vehicles, average fuel economy among new vehicles sold annually gradually declined from 1990 to 2004. The decline in new vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light duty trucks, which grew from about one-fifth of new vehicle sales in the 1970s to slightly over half of the market by 2004. Increasing fuel prices have since decreased the momentum of light duty truck sales, and average new vehicle fuel economy has improved since 2005 as the market share of passenger cars increased. VMT growth among all passenger vehicles has also been impacted, growing an average annual rate of 0.6 percent from 2004 to 2007, compared to an annual rate of 2.6 percent over the period 1990 to 2004.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 29 percent from 1990 to 2007. This rise in CO_2 emissions, combined with an increase in HFCs from virtually no emissions in 1990 to 67.0 Tg CO_2 Eq. in 2007, led to an increase in overall emissions from transportation activities of 28 percent.

Table 2-15: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.)

Vehicle Type/Gas	1990	1995	2000	2005	2006	2007
Passenger Cars	**656.9**	**644.1**	**694.6**	**705.8**	**678.3**	**664.6**
CO_2	628.8	604.9	643.5	658.4	634.4	625.0
CH_4	2.6	2.1	1.6	1.1	1.0	0.9
N_2O	25.4	26.9	25.2	17.8	15.7	13.7
HFCs	+	10.1	24.3	28.5	27.2	24.9
Light-Duty Trucks	**336.2**	**434.7**	**508.3**	**544.8**	**557.1**	**561.7**
CO_2	320.7	405.0	466.2	502.8	515.5	522.0
CH_4	1.4	1.4	1.1	0.7	0.7	0.6
N_2O	14.1	22.1	22.4	13.7	12.6	11.1
HFCs	+	6.1	18.6	27.7	28.3	27.9
Medium- and Heavy-Duty Trucks	**228.8**	**272.7**	**344.2**	**395.1**	**404.5**	**410.8**
CO_2	227.8	271.2	341.3	391.6	401.1	407.4
CH_4	0.2	0.2	0.1	0.1	0.1	0.1
N_2O	0.8	1.0	1.2	1.2	1.1	1.1
HFCs	+	0.3	1.6	2.1	2.2	2.2
Buses	**8.3**	**9.1**	**11.1**	**12.1**	**12.4**	**12.4**
CO_2	8.3	9.0	10.9	11.8	12.1	12.1
CH_4	+	+	+	+	+	+
N_2O	+	+	+	+	+	+
HFCs	+	+	0.1	0.2	0.3	0.3
Motorcycles	**1.8**	**1.8**	**1.9**	**1.6**	**1.9**	**2.1**
CO_2	1.7	1.8	1.8	1.6	1.9	2.0
CH_4	+	+	+	+	+	+
N_2O	+	+	+	+	+	+
Commercial Aircraft[a]	**136.9**	**143.1**	**167.8**	**159.8**	**155.5**	**155.2**
CO_2	135.5	141.6	166.0	158.2	153.9	153.6
CH_4	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	1.3	1.4	1.6	1.5	1.5	1.5
Other Aircraft[b]	**44.4**	**32.3**	**32.9**	**34.5**	**33.8**	**34.2**
CO_2	43.9	32.0	32.5	34.1	33.4	33.9
CH_4	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.4	0.3	0.3	0.3	0.3	0.3
Ships and Boats[c]	**46.9**	**56.6**	**65.1**	**50.7**	**54.1**	**56.3**
CO_2	46.5	55.5	61.0	45.4	48.7	50.8
CH_4	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.4	0.4	0.5	0.4	0.4	0.4
HFCs	+	0.6	3.4	4.7	4.9	4.9
Rail	**38.6**	**44.1**	**50.1**	**56.7**	**58.9**	**58.0**
CO_2	38.1	42.2	45.1	49.8	51.8	50.8
CH_4	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.3	0.3	0.4	0.4	0.4
HFCs	+	1.4	4.6	6.4	6.5	6.6
Other Emissions from Electricity Generation[d]	0.1	0.1	0.1	0.1	0.1	0.1

Table 2-15: Transportation-Related Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Vehicle Type/Gas	1990	1995	2000	2005	2006	2007
Pipelines[e]	**36.2**	**38.5**	**35.2**	**32.4**	**32.6**	**34.6**
CO_2	36.2	38.5	35.2	32.4	32.6	34.6
Lubricants	**11.9**	**11.3**	**12.1**	**10.2**	**9.9**	**10.2**
CO_2	11.9	11.3	12.1	10.2	9.9	10.2
Total Transportation	**1,546.7**	**1,688.3**	**1,923.2**	**2,003.6**	**1,999.0**	**2,000.1**
International Bunker Fuels[f]	*115.6*	*102.7*	*100.0*	*112.7*	*111.7*	*109.9*

+ Does not exceed 0.05 Tg CO_2 Eq.

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

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

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption, and may reflect data collection problems.

[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 limestone and dolomite use (from pollution control equipment installed in electricity generation plants).

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

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

Note: Totals may not sum due to independent rounding. Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8500 lbs; medium- and heavy-duty trucks include vehicles 8501 lbs and above.

HFC emissions primarily reflect HFC-134a.

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, while wastewater treatment emissions have increased 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 agricultural sector includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2007, enteric fermentation was the largest source of CH_4 emissions in the United States, and agricultural soil management was the largest source of N_2O emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors.

Electricity Generation

The process of generating electricity, for consumption in the above sectors, is the single largest source of greenhouse gas emissions in the United States, representing 34 percent of total U.S. emissions. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 42 percent in 2007. Electricity was consumed primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air-conditioning.

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*, EPA expands upon the standard IPCC sectors common for UNFCCC reporting. EPA believes that discussing greenhouse gas emissions relevant to U.S.-specific sectors improves communication of the report's findings.

Electricity Generation: Carbon dioxide 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 CH_4 and N_2O are also based on the EIA electric-utility sector. Additional sources include CO_2 and N_2O 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 SF_6 from electrical transmission and distribution, and a portion of CO_2 from limestone and dolomite use (from pollution control equipment installed in electricity generation plants).

Transportation: Carbon dioxide 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). Additional emissions are apportioned from CH_4 and N_2O from mobile combustion, based on the EIA transportation sector. Substitutes for ozone depleting substances are apportioned to this economic sector based on their specific end-uses within the source category, along with emissions from transportation refrigeration/air-conditioning systems. Finally, CO_2 emissions from non-energy uses of fossil fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

Industry: Carbon dioxide 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. Stationary and mobile combustion emissions of CH_4 and N_2O are also based on the EIA industrial sector, minus emissions apportioned to the Agriculture economic sector described below. Substitutes for ozone depleting substances are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector (emissions from the other economic sectors are subtracted to avoid double-counting). Additionally, all process-related emissions from sources with methods considered within the IPCC Industrial Process guidance have been apportioned to this economic sector. This includes the process-related emissions (i.e., emissions resulting from the processes used to make materials, and not from burning fuels to provide power or heat) 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 CO_2 emissions from limestone and dolomite use (from pollution control equipment installed in large industrial facilities) are also included in the Industry economic sector. Finally, all remaining CO_2 emissions from non-energy uses of fossil fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above), and are attributed to the Industry economic sector.

Agriculture: As agricultural equipment is included in EIA's industrial fuel-consuming sector surveys, additional data is used to separate out 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 CO_2 emissions from fossil fuel combustion and CH_4 and N_2O emissions from stationary and mobile combustion (this data is subtracted from the Industry economic sector to avoid double-counting). The other emission sources included in this economic sector are non-combustion sources of emissions that are included in the Agriculture and Land Use, Land-Use Change and Forestry chapters: N_2O emissions from agricultural soils, CH_4 from enteric fermentation (i.e., exhalation from the digestive tracts of domesticated animals), CH_4 and N_2O from manure management, CH_4 from rice cultivation, CO_2 emissions from liming of agricultural soils and urea application, and CH_4 and N_2O from forest fires. Nitrous oxide emissions from the application of fertilizers to tree plantations (termed "forest land" by the IPCC) are also included in the Agriculture economic sector.

Residential: This economic sector includes the CO_2 emissions from the combustion of fossil fuels reported for the EIA residential sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Substitutes for ozone depleting substances are apportioned based on their specific end-uses within the source category, with emissions from residential air-conditioning systems distributed to this economic sector. Nitrous oxide emissions from the application of fertilizers to developed land (termed "settlements" by the IPCC) are also included in the Residential economic sector.

Commercial: This economic sector includes the CO_2 emissions from the combustion of fossil fuels reported in the EIA commercial fuel-consuming sector data. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA commercial sector. Substitutes for ozone depleting substances are apportioned based on their specific end-uses within the source category, with emissions from commercial refrigeration/air-conditioning systems distributed to this economic sector. Public works sources including direct CH_4 from landfills and CH_4 and N_2O from wastewater treatment and composting are 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 2007; (4) emissions per unit of total gross domestic product as a measure of national economic activity; or (5) emissions per capita.

Table 2-16 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 0.9 percent since 1990. This rate is slightly slower than that for total energy or fossil fuel consumption and much slower than that for either electricity consumption or overall gross domestic product. Total U.S. greenhouse gas emissions have also grown slightly slower than national population since 1990 (see Figure 2-14).

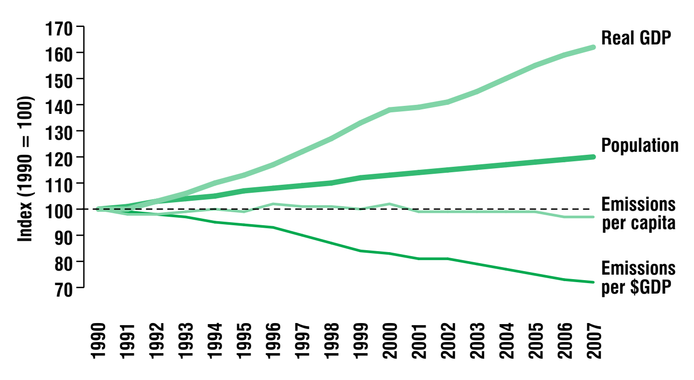
Table 2-16: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	1995	2000	2005	2006	2007	Growth Rate[a]
GDP[b]	100	113	138	155	159	162	2.9%
Electricity Consumption[c]	100	112	127	134	135	137	1.9%
Fossil Fuel Consumption[c]	100	107	117	119	117	119	1.1%
Energy Consumption[c]	100	108	117	119	118	120	1.1%
Population[d]	100	107	113	118	119	120	1.1%
Greenhouse Gas Emissions[e]	100	106	115	117	115	117	0.9%

[a] Average annual growth rate
[b] Gross Domestic Product in chained 2000 dollars (BEA 2008)
[c] Energy content-weighted values (EIA 2008a)
[d] U.S. Census Bureau (2008)
[e] GWP-weighted values

Figure 2-14

U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2008), U.S. Census Bureau (2008), and emission estimates in the this report.

2.3. Indirect Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[7] request that information be provided on indirect greenhouse gases, which include CO, NO_x, NMVOCs, and SO_2. 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 SO_2, by affecting the absorptive characteristics of the atmosphere. Additionally, some of these gases may react with other chemical compounds in the atmosphere to form compounds that are greenhouse gases. Carbon monoxide is produced when carbon-containing fuels are combusted incompletely. Nitrogen oxides (i.e., NO and NO_2) are created by lightning, fires, fossil fuel combustion, and in the stratosphere from N_2O. Non-CH_4 volatile organic compounds—which include hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry. Sulfur-containing compounds emitted into the atmosphere tend to exert a negative radiative forcing (i.e., cooling) and therefore are discussed separately.

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

Since 1970, the United States has published estimates of annual emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2005),[8] which are regulated under the Clean Air Act. Table 2-17 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.

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 87 percent in 2007. 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.

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[7] See <http://unfccc.int/resource/docs/cop8/08.pdf>.

[8] NO_x and CO emission estimates from field burning of agricultural residues were estimated separately, and therefore not taken from EPA (2008).

Table 2-17: Emissions of NO_x, CO, NMVOCs, and SO_2 (Gg)

Gas/Activity	1990	1995	2000	2005	2006	2007
NO_x	**21,450**	**21,070**	**19,004**	**15,612**	**14,701**	**14,250**
Mobile Fossil Fuel Combustion	10,920	10,622	10,310	8,757	8,271	7,831
Stationary Fossil Fuel Combustion	9,689	9,619	7,802	5,857	5,445	5,445
Industrial Processes	591	607	626	534	527	520
Oil and Gas Activities	139	100	111	321	316	314
Incineration of Waste	82	88	114	98	98	97
Agricultural Burning	28	29	35	39	38	37
Solvent Use	1	3	3	5	5	5
Waste	0	1	2	2	2	2
CO	**130,461**	**109,032**	**92,776**	**71,672**	**67,453**	**63,875**
Mobile Fossil Fuel Combustion	119,360	97,630	83,559	62,519	58,322	54,678
Stationary Fossil Fuel Combustion	5,000	5,383	4,340	4,778	4,792	4,792
Industrial Processes	4,125	3,959	2,216	1,744	1,743	1,743
Incineration of Waste	978	1,073	1,670	1,439	1,438	1,438
Agricultural Burning	691	663	792	860	825	892
Oil and Gas Activities	302	316	146	324	323	323
Waste	1	2	8	7	7	7
Solvent Use	5	5	45	2	2	2
NMVOCs	**20,930**	**19,520**	**15,227**	**14,562**	**14,129**	**13,747**
Mobile Fossil Fuel Combustion	10,932	8,745	7,229	6,292	5,954	5,672
Solvent Use	5,216	5,609	4,384	3,881	3,867	3,855
Industrial Processes	2,422	2,642	1,773	2,035	1,950	1,878
Stationary Fossil Fuel Combustion	912	973	1,077	1,450	1,470	1,470
Oil and Gas Activities	554	582	388	545	535	526
Incineration of Waste	222	237	257	243	239	234
Waste	673	731	119	115	113	111
Agricultural Burning	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**16,891**	**14,830**	**13,348**	**12,259**	**11,725**
Stationary Fossil Fuel Combustion	18,407	14,724	12,849	11,641	10,650	10,211
Industrial Processes	1,307	1,117	1,031	852	845	839
Mobile Fossil Fuel Combustion	793	672	632	600	520	442
Oil and Gas Activities	390	335	287	233	221	210
Incineration of Waste	38	42	29	22	22	22
Waste	0	1	1	1	1	1
Solvent Use	0	1	1	0	0	0
Agricultural Burning	NA	NA	NA	NA	NA	NA

NA (Not Available)
Note: Totals may not sum due to independent rounding.
Source: EPA (2005) except for estimates from field burning of agricultural residues.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 86.3 percent of total emissions on a carbon dioxide (CO_2) equivalent basis in 2007. This included 97, 35, and 14 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 83 percent of national emissions from all sources on a CO_2 equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (4 percent collectively).

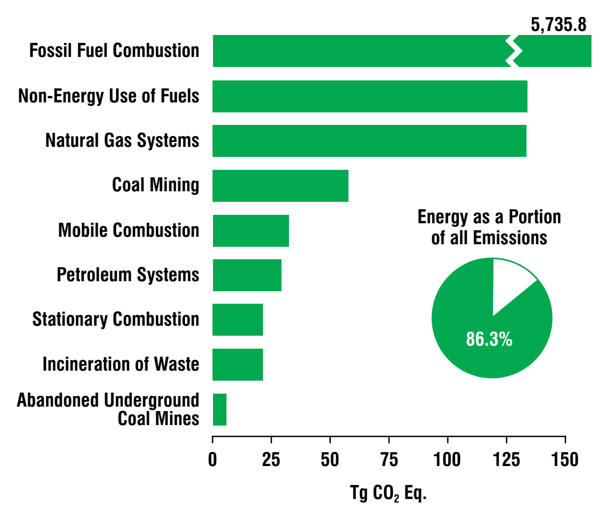
Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1). Globally, approximately 29,195 teragrams (Tg) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2006, of which the United States accounted for about 20 percent.[1] Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered separately, and in more detail than other energy-related emissions (see Figure 3-2). Fossil fuel combustion also emits CH_4 and N_2O, as well as indirect greenhouse gases such as nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs). Mobile fossil fuel combustion was the second largest source of N_2O emissions in the United States, and overall energy-related activities were collectively the largest source of these indirect greenhouse gas emissions.

Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 from natural gas systems, petroleum systems, and coal mining. Smaller quantities of CO_2, CO, NMVOCs, and NO_x are also emitted.

The combustion of biomass and biomass-based fuels also emits greenhouse gases. Carbon dioxide emissions from these activities, however, are not included in national emissions totals because biomass fuels are of biogenic origin. It is assumed that the C released during the consumption of biomass is recycled as U.S. forests and crops regenerate, causing no net addition of CO_2 to the atmosphere. The net impacts of land-use and forestry activities on the C cycle are accounted for separately within the Land Use, Land-Use Change, and Forestry chapter. Emissions of other greenhouse gases from the combustion

Figure 3-1

2007 Energy Chapter Greenhouse Gas Emission Sources



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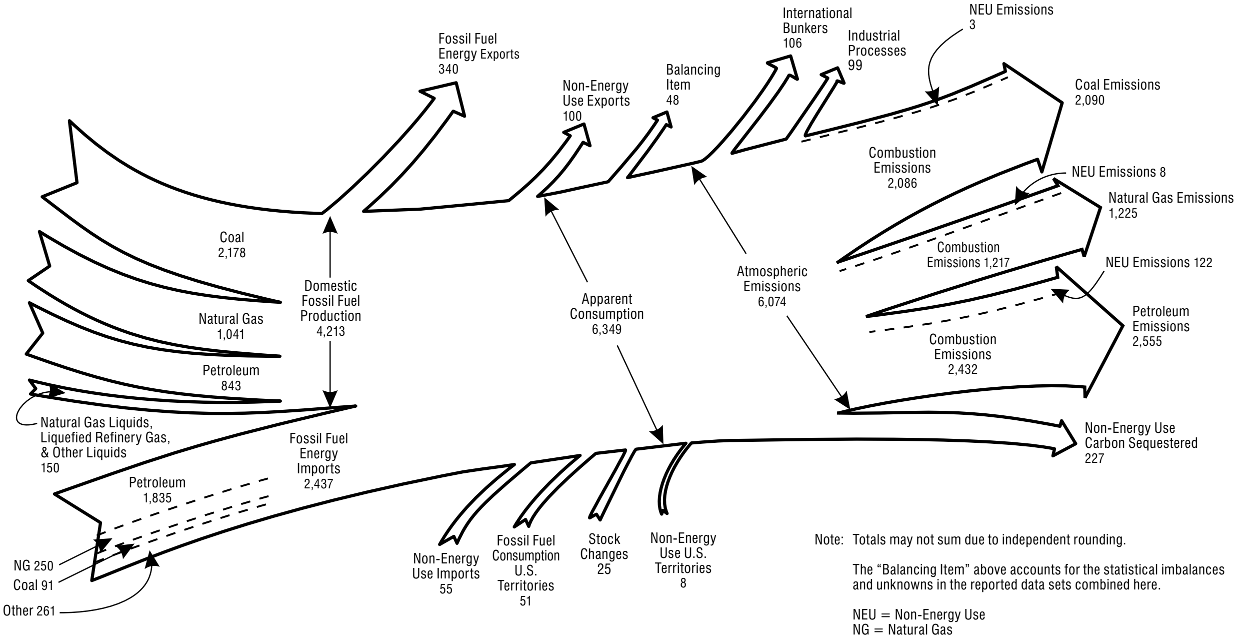
[1] Global CO_2 emissions from fossil fuel combustion were taken from Energy Information Administration *International Energy Annual 2006* <http://www.eia.doe.gov/emeu/iea/carbon.html> EIA (2008).

Figure 3-2

2007 U.S. Fossil Carbon Flows (Tg CO_2 Eq.)



Note: Totals may not sum due to independent rounding.

The “Balancing Item” above accounts for the statistical imbalances and unknowns in the reported data sets combined here.

NEU = Non-Energy Use
NG = Natural Gas

of biomass and biomass-based fuels are included in national totals under stationary and mobile combustion.

Table 3-1 summarizes emissions from the Energy sector in units of Tg of CO_2 equivalents (Tg CO_2 Eq.), while unweighted gas emissions in gigagrams (Gg) are provided in Table 3-2. Overall, emissions due to energy-related activities were 6,170.3 Tg CO_2 Eq. in 2007, an increase of 19 percent since 1990.

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

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**4,871.0**	**5,201.2**	**5,753.2**	**5,910.8**	**5,830.2**	**5,919.5**
Fossil Fuel Combustion	4,708.9	5,013.9	5,561.5	5,723.5	5,635.4	5,735.8
Electricity Generation	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
Transportation	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
Industrial	834.2	862.6	844.6	828.0	844.5	845.4
Residential	337.7	354.4	370.4	358.0	321.9	340.6
Commercial	214.5	224.4	226.9	221.8	206.0	214.4
U.S. Territories	28.3	35.0	36.2	53.2	54.8	50.8
Non-Energy Use of Fuels	117.0	137.5	144.5	138.1	145.1	133.9
Natural Gas Systems	33.7	33.8	29.4	29.5	29.5	28.7
Incineration of Waste	10.9	15.7	17.5	19.5	19.8	20.8
Petroleum Systems	0.4	0.3	0.3	0.3	0.3	0.3
Wood Biomass and Ethanol Consumption[a]	*219.3*	*236.8*	*227.3*	*231.5*	*240.4*	*247.8*
International Bunker Fuels[a]	*114.3*	*101.6*	*99.0*	*111.5*	*110.5*	*108.8*

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

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**265.7**	**251.4**	**239.0**	**206.5**	**205.7**	**205.7**
Natural Gas Systems	129.6	132.6	130.8	106.3	104.8	104.7
Coal Mining	84.1	67.1	60.5	57.1	58.4	57.6
Petroleum Systems	33.9	32.0	30.3	28.3	28.3	28.8
Stationary Combustion	7.4	7.1	6.6	6.7	6.3	6.6
Abandoned Underground Coal Mines	6.0	8.2	7.4	5.6	5.5	5.7
Mobile Combustion	4.7	4.3	3.4	2.5	2.4	2.3
International Bunker Fuels[a]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**57.0**	**67.5**	**67.7**	**51.9**	**48.5**	**45.2**
Mobile Combustion	43.7	53.7	52.8	36.7	33.5	30.1
Stationary Combustion	12.8	13.3	14.5	14.8	14.5	14.7
Incineration of Waste	0.5	0.5	0.4	0.4	0.4	0.4
International Bunker Fuels[a]	*1.1*	*0.9*	*0.9*	*1.0*	*1.0*	*1.0*
Total	**5,193.6**	**5,520.1**	**6,059.9**	**6,169.2**	**6,084.4**	**6,170.3**

[a] These values are presented for informational purposes only and are not included or are already accounted for in totals.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**4,870,953**	**5,201,233**	**5,753,192**	**5,910,830**	**5,830,206**	**5,919,452**
Fossil Fuel Combustion	4,708,918	5,013,910	5,561,515	5,723,477	5,635,418	5,735,789
Non-Energy Use of Fuels	116,977	137,460	144,473	138,070	145,137	133,910
Natural Gas Systems	33,733	33,810	29,394	29,463	29,540	28,680
Incineration of Waste	10,950	15,712	17,485	19,532	19,824	20,786
Petroleum Systems	376	341	325	287	288	287
Wood Biomass and Ethanol Consumption[a]	*219,341*	*236,775*	*227,276*	*231,481*	*240,386*	*247,829*
International Bunker Fuels[a]	*114,330*	*101,620*	*98,966*	*111,487*	*110,520*	*108,756*
CH_4	**12,651**	**11,970**	**11,381**	**9,832**	**9,795**	**9,796**
Natural Gas Systems	6,171	6,314	6,231	5,062	4,991	4,985
Coal Mining	4,003	3,193	2,881	2,719	2,780	2,744
Petroleum Systems	1,613	1,524	1,441	1,346	1,346	1,370
Stationary Combustion	352	340	315	318	300	315
Abandoned Underground Coal Mines	288	392	350	265	263	273
Mobile Combustion	225	207	163	121	115	109
International Bunker Fuels[a]	*8*	*6*	*6*	*7*	*7*	*7*
N_2O	**184**	**218**	**219**	**167**	**156**	**146**
Mobile Combustion	141	173	170	118	108	97
Stationary Combustion	41	43	47	48	47	47
Incineration of Waste	2	1	1	1	1	1
International Bunker Fuels[a]	*3*	*3*	*3*	*3*	*3*	*3*

[a] These values are presented for informational purposes only and are not included or are already accounted for in totals.

Note: Totals may not sum due to independent rounding.

3.1. Fossil Fuel Combustion (IPCC Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. Following that is a discussion of emissions of all three gases from fossil fuel combustion presented by sectoral breakdowns. Methodologies for estimating CO_2 from fossil fuel combustion also differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2007, CO_2 emissions from fossil fuel combustion increased by 1.8 percent relative to the previous year. This increase is primarily a result of an increase in electricity demand, combined with a significant decrease (14.2 percent) in hydropower generation used to meet this demand. Additionally, cooler winter and warmer summer conditions in 2007 increased the demand for heating fuels and contributed to the increase in the demand for electricity. In 2007, CO_2 emissions from fossil fuel combustion were 5,735.8 Tg CO_2 Eq., or 22 percent above emissions in 1990 (see Table 3-5).[2]

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

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

Gas	1990	1995	2000	2005	2006	2007
CO_2	4,708.9	5,013.9	5,561.5	5,723.5	5,635.4	5,735.8
CH_4	12.1	11.5	10.0	9.2	8.7	8.9
N_2O	56.5	67.0	67.4	51.5	48.1	44.8
Total	**4,777.6**	**5,092.4**	**5,638.9**	**5,784.2**	**5,692.2**	**5,789.5**

Note: Totals may not sum due to independent rounding.

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

Gas	1990	1995	2000	2005	2006	2007
CO_2	4,708,918	5,013,910	5,561,515	5,723,477	5,635,418	5,735,789
CH_4	578	547	478	439	415	424
N_2O	182	216	217	166	155	145

Note: Totals may not sum due to independent rounding.

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

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

Fuel/Sector	1990	1995	2000	2005	2006	2007
Coal	**1,695.9**	**1,801.9**	**2,046.4**	**2,088.2**	**2,057.2**	**2,086.5**
Residential	2.9	1.7	1.0	0.8	0.5	0.6
Commercial	11.8	11.1	8.2	9.1	6.2	6.8
Industrial	149.5	139.6	126.8	116.2	114.1	107.4
Transportation	NE	NE	NE	NE	NE	NE
Electricity Generation	1,531.1	1,648.6	1,909.5	1,958.4	1,932.4	1,967.6
U.S. Territories	0.6	0.9	0.9	3.7	4.0	4.1
Natural Gas	**1,001.7**	**1,159.1**	**1,210.8**	**1,161.4**	**1,140.7**	**1,216.5**
Residential	237.4	262.3	268.8	262.0	236.8	256.9
Commercial	141.5	164.0	171.6	163.1	153.8	163.4
Industrial	410.1	465.0	452.3	381.8	376.2	385.6
Transportation	36.2	38.6	35.6	33.2	33.5	35.4
Electricity Generation	176.5	229.2	281.8	319.9	338.9	373.8
U.S. Territories	NO	NO	0.7	1.3	1.4	1.4
Petroleum	**2,010.9**	**2,052.6**	**2,303.9**	**2,473.5**	**2,437.2**	**2,432.4**
Residential	97.4	90.5	100.5	95.2	84.5	83.2
Commercial	61.2	49.3	47.2	49.6	46.0	44.2
Industrial	274.6	257.9	265.5	330.0	354.2	352.5
Transportation	1,448.3	1,560.1	1,764.7	1,848.2	1,847.4	1,852.0
Electricity Generation	101.8	60.7	91.5	102.3	55.6	55.3
U.S. Territories	27.6	34.0	34.6	48.2	49.4	45.3
Geothermal[a]	**0.40**	**0.34**	**0.36**	**0.38**	**0.37**	**0.38**
Total	**4,708.9**	**5,013.9**	**5,561.5**	**5,723.5**	**5,635.4**	**5,735.8**

NE (Not Estimated)
NO (Not Occurring)
[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes.
Note: Totals may not sum due to independent rounding.

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 as much C per unit of energy as coal, and natural gas has only about 55 percent.[3] Producing a unit of heat or electricity using natural gas instead of coal can reduce the CO_2 emissions associated with energy consumption, and using nuclear or renewable energy sources (e.g., wind) can essentially eliminate emissions (see Box 3-2). Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

In the United States, 85 percent of the energy consumed in 2007 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 (7 percent), primarily hydroelectric power and biofuels (EIA 2008a). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for an average of 42 percent of total fossil-fuel-based energy consumption in 2007. Natural gas and coal followed in order of importance, accounting for 30 and 28 percent of total consumption, respectively. Petroleum was consumed primarily in the transportation end-use sector, the vast majority of coal was used in electricity generation, and natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-5) (EIA 2008a).

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

Table 3-6: Annual Change in CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (Tg CO_2 Eq. and Percent)

Sector	Fuel Type	2003 to 2004		2004 to 2005		2005 to 2006		2006 to 2007	
Electricity Generation	Coal	11.4	0.6%	40.8	2.1%	-26.0	-1.3%	35.3	1.8%
Electricity Generation	Natural Gas	18.4	6.6%	22.7	7.6%	19.0	5.9%	34.9	10.3%
Electricity Generation	Petroleum	2.0	2.0%	2.2	2.2%	-46.7	-45.6%	-0.3	-0.6%
Transportation[a]	Petroleum	51.1	2.9%	19.9	1.1%	-0.8	0.0%	4.6	0.2%
Residential	Natural Gas	-13.7	-4.9%	-0.5	-0.2%	-25.2	-9.6%	20.1	8.5%
Commercial	Natural Gas	-5.1	-2.9%	-5.7	-3.4%	-9.3	-5.7%	9.6	6.2%
Industrial	Coal	1.2	1.0%	-2.4	-2.0%	-2.1	-1.8%	-6.7	-5.9%
Industrial	Natural Gas	-17.8	-4.2%	-28.3	-6.9%	-5.6	-1.5%	9.4	2.5%
All Sectors[b]	**All Fuels[b]**	**64.4**	**1.1%**	**54.2**	**1.0%**	**-88.1**	**-1.5%**	**100.4**	**1.8%**

[a] Excludes emissions from International Bunker Fuels.
[b] Includes fuels and sectors not shown in table.

Figure 3-3

2007 U.S. Energy Consumption by Energy Source

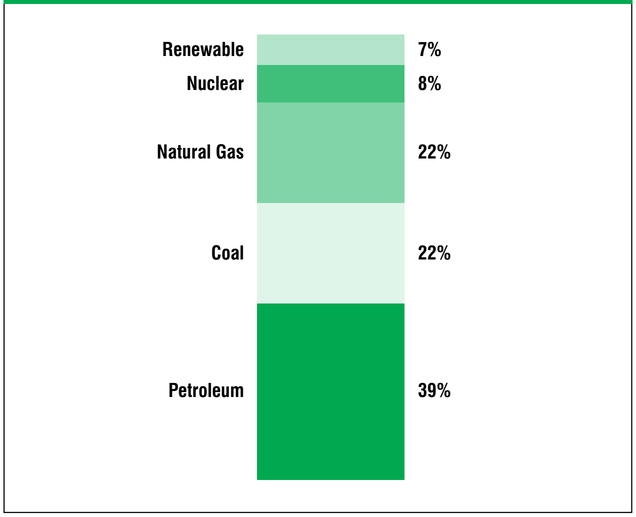
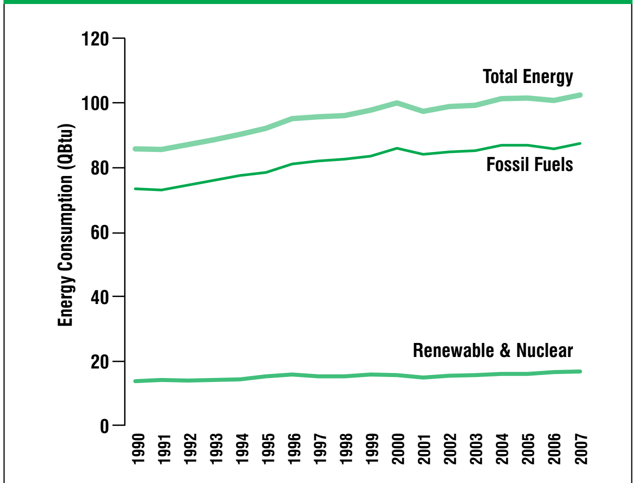


Figure 3-4

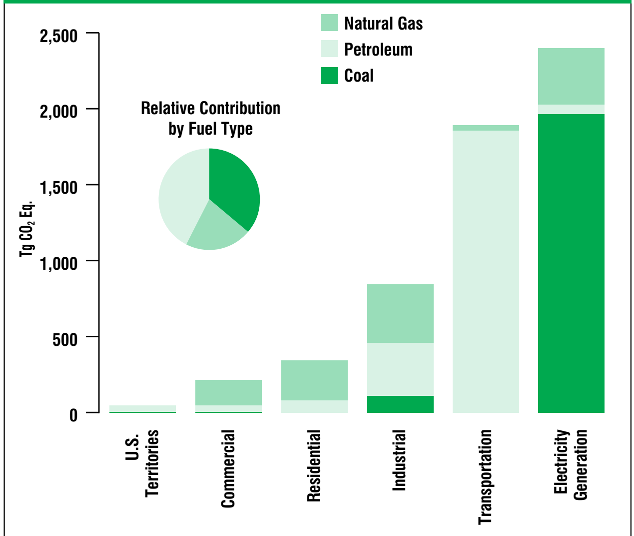
U.S. Energy Consumption (Quadrillion Btu)



Note: Expressed as gross calorific values.

Figure 3-5

2007 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Note: Electricity generation also includes emissions of less than 0.5 Tg CO_2 Eq. from geothermal-based electricity generation.

Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, CO, and NMVOCs.[4] These other C containing non-CO_2 gases are emitted as a by-product of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, it is assumed that all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

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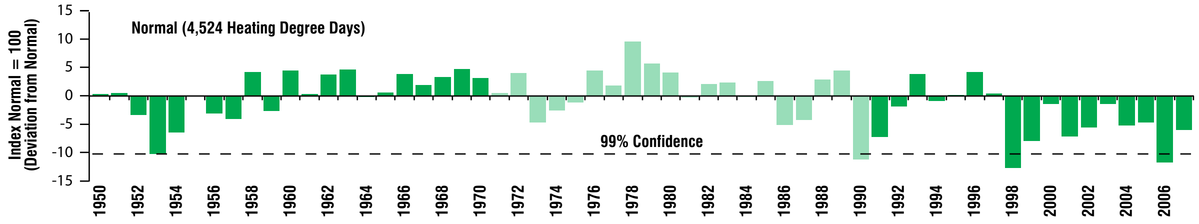
[4] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

Box 3-1: Weather and Non-Fossil Energy Effects on CO_2 from Fossil Fuel Combustion Trends

In 2007, weather conditions became much cooler in the winter and slightly warmer in the summer, compared to 2006. Although winter conditions were cooler in 2007 compared to 2006, the winter was warmer than normal, with heating degree days in the United States 6 percent below normal (see Figure 3-6). Cooler winter conditions compared to 2006 led to an increase in demand for heating fuels. Although summer conditions were slightly warmer in 2007 compared to 2006, summer temperatures were substantially warmer than usual, with cooling degree days 13 percent above normal (see Figure 3-7) (EIA 2008f).[5] As a result, the demand for electricity increased due to warmer summer conditions compared to 2006.

Figure 3-6

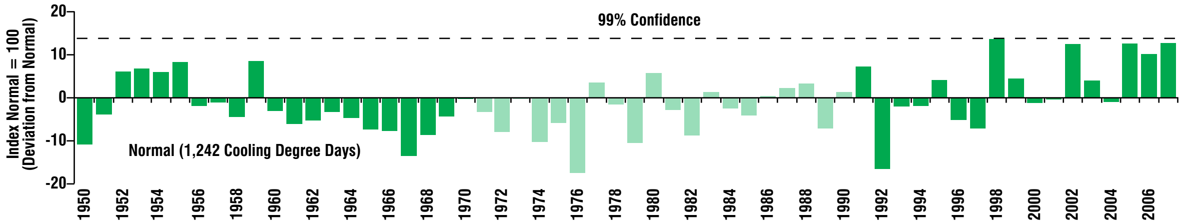
Annual Deviations from Normal Heating Degree Days for the United States (1950–2007)



Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1971 through 1990.

Figure 3-7

Annual Deviations from Normal Cooling Degree Days for the United States (1950–2007)

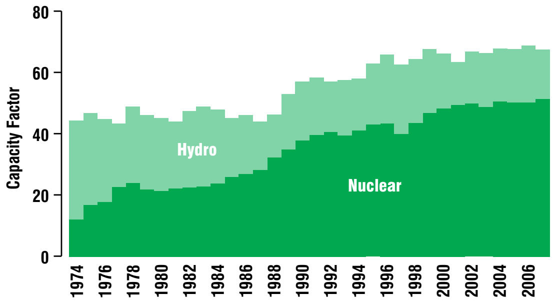


Note: Climatological normal data are highlighted. Statistical confidence interval for "normal" climatology period of 1971 through 1990.

Although no new U.S. nuclear power plants have been constructed in recent years, the utilization (i.e., capacity factors[6]) of existing plants in 2007 remained high at just over 90 percent. Electricity output by hydroelectric power plants decreased in 2007 by approximately 14 percent. Electricity generated by nuclear plants in 2007 provided almost 3 times as much of the energy consumed in the United States as hydroelectric plants (EIA 2008a). Aggregate nuclear and hydroelectric power plant capacity factors since 1973 are shown in Figure 3-8.

Figure 3-8

Aggregate Nuclear and Hydroelectric Power Plant Capacity Factors in the United States (1974–2007)



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[5] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65° F, while cooling degree days are deviations of the mean daily temperature above 65° F. 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).

[6] The capacity factor is defined as the ratio of the electrical energy produced by a generating unit for a given period of time to the electrical energy that could have been produced at continuous full-power operation during the same period (EIA 2008a).

Fossil Fuel Combustion Emissions by Sector

In addition to the CO_2 emitted from fossil fuel combustion, CH_4 and N_2O are emitted from stationary and mobile combustion as well. Table 3-7 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector.

Other than CO_2, gases emitted from stationary combustion include the greenhouse gases CH_4 and N_2O and the indirect greenhouse gases NO_x, CO, and NMVOCs.[7] CH_4 and N_2O 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 CH_4 content of the fuel and combustion efficiency.

Mobile combustion produces greenhouse gases other than CO_2, including CH_4, N_2O, and indirect greenhouse gases including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in idle, low speed, and cold start conditions. Methane and

Table 3-7: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (Tg CO_2 Eq.)

End-Use Sector/Gas	1990	1995	2000	2005	2006	2007
Electricity Generation	**1,818.3**	**1,948.0**	**2,293.8**	**2,392.1**	**2,338.1**	**2,408.2**
CO_2	1,809.7	1,938.9	2,283.2	2,381.0	2,327.3	2,397.2
CH_4	0.6	0.6	0.7	0.7	0.7	0.7
N_2O	8.1	8.6	10.0	10.3	10.1	10.3
Transportation	**1,532.9**	**1,656.7**	**1,856.5**	**1,920.7**	**1,916.8**	**1,919.8**
CO_2	1,484.5	1,598.7	1,800.3	1,881.5	1,880.9	1,887.4
CH_4	4.7	4.3	3.4	2.5	2.4	2.3
N_2O	43.7	53.7	52.8	36.7	33.5	30.1
Industrial	**838.9**	**867.5**	**849.4**	**832.5**	**849.2**	**849.9**
CO_2	834.2	862.6	844.6	828.0	844.5	845.4
CH_4	1.5	1.6	1.6	1.5	1.5	1.5
N_2O	3.2	3.3	3.2	3.1	3.2	3.1
Residential	**343.2**	**359.4**	**374.7**	**362.5**	**325.9**	**345.1**
CO_2	337.7	354.4	370.4	358.0	321.9	340.6
CH_4	4.4	4.0	3.4	3.5	3.2	3.5
N_2O	1.1	1.0	0.9	0.9	0.8	0.9
Commercial	**215.8**	**225.7**	**228.2**	**223.0**	**207.2**	**215.5**
CO_2	214.5	224.4	226.9	221.8	206.0	214.4
CH_4	0.9	0.9	0.9	0.9	0.8	0.8
N_2O	0.4	0.4	0.3	0.3	0.3	0.3
U.S. Territories[a]	**28.4**	**35.1**	**36.3**	**53.4**	**55.0**	**51.0**
Total	**4,777.6**	**5,092.4**	**5,638.9**	**5,784.2**	**5,692.2**	**5,789.5**

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

Note: 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.

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

NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electricity generation to the sectors in which it is used. Four end-use sectors were defined: industrial, transportation, residential, and commercial. In Table 3-8, 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 CH_4 and N_2O from transportation.[8] Emissions from U.S. territories are also calculated separately due to a lack of end-use-specific consumption data. This method of distributing emissions assumes that each sector consumes electricity generated from an equally carbon-intensive mix of fuels and other energy sources. Table 3-7 and Table 3-8 summarize CO_2, CH_4, and N_2O emissions from direct fossil fuel combustion and pro-rated electricity generation emissions from electricity consumption by end-use sector. The following discussions for stationary combustion sources focus on direct emissions, as presented in Table 3-7, while the discussion of transportation and mobile combustion sources focuses on the alternative method as presented in Table 3-8.

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 CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see Methodology section for CO_2 from fossil fuel combustion). Other than CO_2, gases emitted from stationary combustion include the greenhouse gases CH_4 and N_2O. Table 3-10 and Table 3-11 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. Methane and N_2O emissions from stationary

Table 3-8: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector (Tg CO_2 Eq.)[a]

End-Use Sector/Gas	1990	1995	2000	2005	2006	2007
Transportation	**1,536.0**	**1,659.7**	**1,860.0**	**1,925.4**	**1,921.3**	**1,924.6**
CO_2	1,487.5	1,601.7	1,803.7	1,886.2	1,885.4	1,892.2
CH_4	4.7	4.3	3.4	2.5	2.4	2.3
N_2O	43.7	53.7	52.8	36.7	33.6	30.1
Industrial	**1,524.7**	**1,583.8**	**1,638.1**	**1,566.4**	**1,558.7**	**1,561.2**
CO_2	1,516.8	1,575.5	1,629.6	1,558.5	1,550.7	1,553.4
CH_4	1.7	1.8	1.8	1.7	1.7	1.7
N_2O	6.2	6.5	6.7	6.2	6.2	6.1
Residential	**935.4**	**1,001.3**	**1,136.1**	**1,215.6**	**1,153.8**	**1,206.4**
CO_2	927.1	993.3	1,128.2	1,207.2	1,145.9	1,198.0
CH_4	4.6	4.2	3.6	3.8	3.4	3.8
N_2O	3.7	3.8	4.2	4.6	4.4	4.6
Commercial	**753.0**	**812.5**	**968.5**	**1,023.3**	**1,003.4**	**1,046.4**
CO_2	749.2	808.5	963.8	1,018.4	998.6	1,041.4
CH_4	1.0	1.1	1.1	1.1	1.1	1.1
N_2O	2.8	2.9	3.6	3.8	3.7	3.9
U.S. Territories[b]	**28.4**	**35.1**	**36.3**	**53.4**	**55.0**	**51.0**
Total	**4,777.6**	**5,092.4**	**5,638.9**	**5,784.2**	**5,692.2**	**5,789.5**

[a] Electricity generation emissions have been distributed to each end-use sector based upon the sector's share of national electricity consumption.
[b] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.
Note: 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.

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[8] Separate calculations were performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions are discussed in the mobile combustion section.

Table 3-9: CO_2 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	2000	2005	2006	2007
Electricity Generation	**1,809.7**	**1,938.9**	**2,283.2**	**2,381.0**	**2,327.3**	**2,397.2**
Coal	1,531.1	1,648.6	1,909.5	1,958.4	1,932.4	1,967.6
Natural Gas	176.5	229.2	281.8	319.9	338.9	373.8
Fuel Oil	101.8	60.7	91.5	102.3	55.6	55.3
Geothermal	0.4	0.3	0.4	0.4	0.4	0.4
Industrial	**834.2**	**862.6**	**844.6**	**828.0**	**844.5**	**845.4**
Coal	149.5	139.6	126.8	116.2	114.1	107.4
Natural Gas	410.1	465.0	452.3	381.8	376.2	385.6
Fuel Oil	274.6	257.9	265.5	330.0	354.2	352.5
Commercial	**214.5**	**224.4**	**226.9**	**221.8**	**206.0**	**214.4**
Coal	11.8	11.1	8.2	9.1	6.2	6.8
Natural Gas	141.5	164.0	171.6	163.1	153.8	163.4
Fuel Oil	61.2	49.3	47.2	49.6	46.0	44.2
Residential	**337.7**	**354.4**	**370.4**	**358.0**	**321.9**	**340.6**
Coal	2.9	1.7	1.0	0.8	0.5	0.6
Natural Gas	237.4	262.3	268.8	262.0	236.8	256.9
Fuel Oil	97.4	90.5	100.5	95.2	84.5	83.2
U.S. Territories[a]	**28.3**	**35.0**	**36.2**	**53.2**	**54.8**	**50.8**
Coal	0.6	0.9	0.9	3.7	4.0	4.1
Natural Gas	NO	NO	0.7	1.3	1.4	1.4
Fuel Oil	27.6	34.0	34.6	48.2	49.4	45.3
Total	**4,708.9**	**5,013.9**	**5,561.5**	**5,723.5**	**5,635.4**	**5,735.8**

NO (Not Occurring)

[a] U.S. Territories are not apportioned by sector, and emissions from all fuel combustion sources are presented in this table.

Note: Totals may not sum due to independent rounding.

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 CH_4 content of the fuel and combustion efficiency. Please refer to Table 3-7 for the corresponding presentation of all direct emission sources of fuel combustion.

Electricity Generation

The process of generating electricity is the single largest source of CO_2 emissions in the United States, representing 39 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of emissions from electricity generation, representing less than 0.1 percent and 0.4 percent, respectively. Electricity generation also accounted for the largest share of CO_2 emissions from fossil fuel combustion, approximately 42 percent in 2007. Methane and N_2O from electricity generation represented 8 and 23 percent of emissions from fossil fuel combustion in 2007. 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).

The electric power industry includes all power producers, consisting of both regulated utilities and nonutilities (e.g. independent power producers, qualifying cogenerators, 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

Table 3-10: CH_4 Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	2000	2005	2006	2007
Electricity Generation	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**
Coal	0.3	0.4	0.4	0.4	0.4	0.4
Fuel Oil	0.1	+	0.1	0.1	+	+
Natural Gas	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
Industrial	**1.5**	**1.6**	**1.6**	**1.5**	**1.5**	**1.5**
Coal	0.3	0.3	0.3	0.3	0.3	0.2
Fuel Oil	0.2	0.1	0.1	0.2	0.2	0.2
Natural Gas	0.2	0.2	0.2	0.1	0.1	0.1
Wood	0.9	1.0	1.0	0.9	0.9	0.9
Commercial	**0.9**	**0.9**	**0.9**	**0.9**	**0.8**	**0.8**
Coal	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.3	0.3	0.3	0.3	0.3	0.3
Wood	0.4	0.4	0.4	0.4	0.4	0.4
Residential	**4.4**	**4.0**	**3.4**	**3.5**	**3.2**	**3.5**
Coal	0.2	0.1	0.1	0.1	+	+
Fuel Oil	0.3	0.3	0.3	0.3	0.3	0.3
Natural Gas	0.4	0.5	0.5	0.5	0.4	0.5
Wood	3.5	3.1	2.5	2.7	2.5	2.8
U.S. Territories	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+
Fuel Oil	+	+	+	0.1	0.1	0.1
Natural Gas	+	+	+	+	+	+
Wood	+	+	+	+	+	+
Total	**7.4**	**7.1**	**6.6**	**6.7**	**6.3**	**6.6**

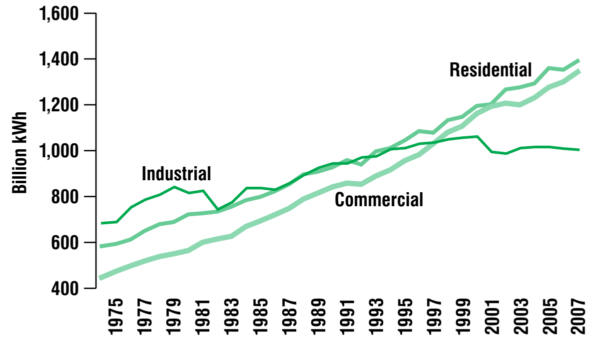
+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

the production of electricity,[9] while the other sectors consist of those producers that indicate their primary business is something other than the production of electricity.

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 2007 increased about 3 percent in the residential and 3.3 percent in the commercial sectors. The trend in the commercial sector can largely be attributed to the growing economy (2.0 percent), which led to increased demand for electricity. The increase is also attributed to an increase in air conditioning-related electricity consumption in the residential and commercial sectors that occurred as a result of the warmer summer compared to 2006. In 2007, the amount of electricity

Figure 3-9

Electricity Generation Retail Sales by End-Use Sector (1974–2007)



Note: The transportation end-use sector consumes minor quantities of electricity.

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[9] 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).

Table 3-11: N_2O Emissions from Stationary Combustion (Tg CO_2 Eq.)

Sector/Fuel Type	1990	1995	2000	2005	2006	2007
Electricity Generation	**8.1**	**8.6**	**10.0**	**10.3**	**10.1**	**10.3**
Coal	7.6	8.1	9.4	9.7	9.5	9.7
Fuel Oil	0.2	0.1	0.2	0.2	0.1	0.1
Natural Gas	0.1	0.1	0.2	0.2	0.2	0.2
Wood	0.2	0.1	0.2	0.2	0.2	0.2
Industrial	**3.2**	**3.3**	**3.2**	**3.1**	**3.2**	**3.1**
Coal	0.7	0.7	0.6	0.6	0.6	0.5
Fuel Oil	0.5	0.4	0.4	0.6	0.6	0.6
Natural Gas	0.2	0.3	0.3	0.2	0.2	0.2
Wood	1.7	1.9	1.9	1.7	1.8	1.7
Commercial	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	0.1	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1
Natural Gas	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
Residential	**1.1**	**1.0**	**0.9**	**0.9**	**0.8**	**0.9**
Coal	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.3	0.3	0.2	0.2
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.7	0.6	0.5	0.5	0.5	0.5
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	+	+	+	+	+	+
Wood	+	+	+	+	+	+
Total	**12.8**	**13.3**	**14.5**	**14.8**	**14.5**	**14.7**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

generated (in kWh) increased by 2.1 percent from the previous year. This growth is due to the growing economy, expanding industrial production, and warmer summer conditions compared to 2006. As a result, CO_2 emissions from the electric power sector increased by 3.0 percent as the consumption of coal and natural gas for electricity generation increased. Coal and natural gas consumption for electricity generation increased by 1.8 percent and 10.3 percent, respectively, in 2007, and nuclear power increased by just over 2 percent. As a result of the significant increase in natural gas consumption, C intensity from direct fossil fuel combustion decreased slightly overall in 2007 (see Table 3-15). Coal is consumed primarily by the electric power sector in the United States, which accounted for 94 percent of total coal consumption for energy purposes in 2007. Spurred by a 14.2-percent decrease in hydropower, total renewable electricity generation fell by 8.9 percent in 2007. However non-hydropower renewable generation grew by 6.8 percent, thus preventing an even greater increase in emissions.

Industrial End-Use Sector

The industrial sector accounted for 15 percent of CO_2 emissions from fossil fuel combustion, 17 percent of CH_4 emissions from fossil fuel combustion, and 7 percent of N_2O emissions from fossil fuel combustion. Carbon dioxide, CH_4, and N_2O 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, primary metals, paper, food, and nonmetallic mineral products—represent the vast majority of the energy use (EIA 2008a and EIA 2005).

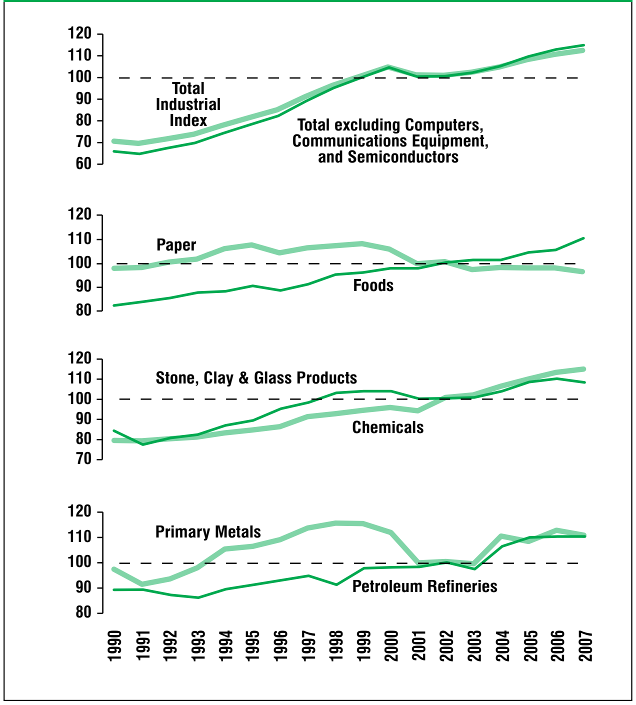
In theory, emissions from the industrial sector should be highly correlated with economic growth and industrial output, but heating of industrial buildings and agricultural energy consumption are also affected by weather conditions.[10] In addition, structural changes within the U.S. economy that lead 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 affect on industrial emissions.

From 2006 to 2007, total industrial production and manufacturing output increased by 1.7 and 1.8 percent, respectively (FRB 2007). Over this period, output increased for chemicals, and food, but decreased for petroleum refineries, paper, primary metals, and nonmetallic mineral products (see Figure 3-10).

Despite the growth in industrial output (60 percent) and the overall U.S. economy (62 percent) from 1990 to 2007, CO_2 emissions from the industrial sector increased by only 1.3 percent over that time. A number of factors are believed to have caused this disparity between rapid growth in industrial output and only minor growth in industrial emissions, including: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) improvements in energy efficiency. In 2007, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sectors totaled 1,561.2 Tg CO_2 Eq., or 0.2 percent above 2006 emissions.

Figure 3-10

Industrial Production Indices (Index 2002=100)



Residential and Commercial End-Use Sectors

The residential and commercial sectors accounted for an average 6 and 4 percent of CO_2 emissions from fossil fuel combustion, 40 and 9 percent of CH_4 emissions from fossil fuel combustion, and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in both of these end-use sectors. In 2007, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 1,206.4 Tg CO_2 Eq. and 1,046.4 Tg CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from the residential sector increased by 4.4 percent in 2007, with emissions in 2007 from the commercial sector 4.1 percent higher than in 2006.

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).

Emissions from natural gas consumption represent over 75 and 76 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. In 2007, natural gas CO_2 emissions increased by 8.5 percent and 6 percent, respectively, in each of these sectors. The increase in emissions in both sectors is a result of cooler winter conditions in the United States compared to 2006.

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[10] 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.

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 CO_2 from fossil fuel combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are presented in Table 3-7 through 3-11, though the emissions will include some transportation and mobile combustion sources.

Transportation 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 electricity consumption), please see Table 3-7.

Transportation End-Use Sector

The transportation end-use sector accounted for 1,924.6 Tg CO_2 Eq. in 2007, which represented 33 percent of CO_2 emissions from fossil fuel combustion, 26 percent of CH_4 emissions from fossil fuel combustion, and 67 percent of N_2O emissions from fossil fuel combustion, respectively. Fuel purchased in the U.S. for international aircraft and marine travel accounted for an additional 108.8 Tg CO_2 in 2007; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols. Among domestic transportation sources, light duty vehicles (including passenger cars and light-duty trucks) represented 61 percent of CO_2 emissions, medium- and heavy-duty trucks 22 percent, commercial aircraft 8 percent, and other sources 10 percent. See Table 3-12 for a detailed breakdown of CO_2 emissions by mode and fuel type.

From 1990 to 2007, transportation emissions rose by 29 percent due, in large part, to increased demand for travel and the stagnation of fuel efficiency across the U.S. vehicle fleet. The number of vehicle miles traveled by light-duty motor vehicles (passenger cars and light-duty trucks) increased 40 percent from 1990 to 2007, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices over much of this period. A similar set of social and economic trends has led to a significant increase in air travel and freight transportation by both air and road modes during the time series.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 29 percent from 1990 to 2007. This rise in CO_2 emissions, combined with an increase in HFCs from virtually no emissions in 1990 to 67.0 Tg CO_2 Eq. in 2007, led to an increase in overall emissions from transportation activities of 28 percent.

Fossil Fuel Combustion CO_2 Emissions from Transportation

Domestic transportation CO_2 emissions increased by 27 percent (404.7 Tg CO_2 Eq.) between 1990 and 2007, an annualized increase of 1.5 percent. Since 2005, the growth rate of emissions has slowed considerably; transportation CO_2 emissions increased by just 0.3 percent in total between 2005 and 2007. Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Transportation sources also produce CH_4 and N_2O; these emissions are included in Table 3-13 and Table 3-14 in the "Mobile Combustion" section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Carbon dioxide emissions from passenger cars and light-duty trucks totaled 1,147.0 Tg CO_2 Eq. in 2007, an increase of 21 percent (197.5 Tg CO_2 Eq.) from 1990. CO_2 emissions from passenger cars and light-duty trucks peaked at 1,181.3 Tg CO_2 Eq.in 2004, and since then have declined about 3 percent. Over the 1990s through early this decade, growth in vehicle

Table 3-12: CO_2 Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (Tg CO_2 Eq.)[a]

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007
Gasoline	**982.7**	**1,038.9**	**1,135.7**	**1181.1**	**1,169.7**	**1,166.7**
Passenger Cars	621.0	597.0	639.9	654.2	630.3	620.9
Light-Duty Trucks	308.9	389.9	446.0	476.0	487.9	493.9
Medium- and Heavy-Duty Trucks[b]	38.7	35.8	36.0	34.7	35.3	35.6
Buses	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	1.7	1.8	1.8	1.6	1.9	2.0
Recreational Boats	12.1	14.1	11.6	14.2	14.0	13.8
Distillate Fuel Oil (Diesel)	**261.2**	**315.9**	**394.7**	**453.0**	**464.7**	**470.6**
Passenger Cars	7.8	7.7	3.6	4.2	4.1	4.1
Light-Duty Trucks	11.3	14.7	19.8	25.5	26.4	26.9
Medium- and Heavy-Duty Trucks[b]	188.3	234.9	305.1	356.5	365.4	371.3
Buses	7.9	8.6	10.1	10.6	10.9	10.9
Rail	35.1	39.2	41.7	45.1	47.3	46.0
Recreational Boats	1.9	2.3	2.7	3.1	3.2	3.3
Ships and Other Boats	8.8	8.6	11.7	8.0	7.4	8.1
International Bunker Fuels[c]	*11.6*	*9.2*	*6.3*	*9.3*	*8.7*	*8.1*
Jet Fuel	**176.2**	**170.9**	**196.1**	**189.9**	**185.0**	**185.3**
Commercial Aircraft	135.5	141.6	166.0	158.2	153.9	153.6
Military Aircraft	34.4	23.9	20.7	17.8	16.1	15.8
General Aviation Aircraft	6.4	5.4	9.3	13.9	15.0	15.8
International Bunker Fuels[c]	*46.4*	*51.2*	*57.7*	*56.4*	*54.6*	*52.7*
Aviation Gasoline	**3.1**	**2.7**	**2.5**	**2.4**	**2.3**	**2.2**
General Aviation Aircraft	3.1	2.7	2.5	2.4	2.3	2.2
Residual Fuel Oil	**23.7**	**30.5**	**34.9**	**20.2**	**24.1**	**25.6**
Ships and Other Boats[d]	23.7	30.5	34.9	20.2	24.1	25.6
International Bunker Fuels[c,d]	*56.4*	*41.2*	*35.0*	*45.8*	*47.2*	*47.9*
Natural Gas	**36.2**	**38.6**	**35.6**	**33.2**	**33.5**	**35.4**
Passenger Cars	+	0.1	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Buses	+	0.1	0.4	0.8	0.8	0.8
Pipelines	36.2	38.5	35.2	32.4	32.6	34.6
LPG	**1.4**	**1.1**	**0.7**	**1.7**	**1.6**	**1.6**
Light-Duty Trucks	0.5	0.5	0.4	1.3	1.2	1.2
Medium- and Heavy-Duty Trucks[b]	0.8	0.5	0.2	0.4	0.5	0.5
Buses	+	+	+	+	+	+
Electricity	**3.0**	**3.0**	**3.4**	**4.7**	**4.5**	**4.8**
Rail	3.0	3.0	3.4	4.7	4.5	4.8
Total	**1,487.5**	**1,601.7**	**1,803.7**	**1,886.2**	**1,885.4**	**1,892.2**
Total (Including Bunkers)[c]	**1,601.8**	**1,703.3**	**1,902.7**	**1,997.6**	**1,995.9**	**2,000.9**

+ Less than 0.05 Tg CO_2 Eq.

[a] 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.

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

[c] 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.

[d] Fluctuations in emission estimates from the combustion of residual fuel oil are associated with fluctuations in reported fuel consumption and may reflect data collection problems.

Note: Totals may not sum due to independent rounding.

travel substantially outweighed improvements in vehicle fuel economy; however, the rate of Vehicle Miles Traveled (VMT) growth slowed considerably starting in 2005 while average vehicle fuel economy increased. Among new vehicles sold annually, average fuel economy gradually declined from 1990 to 2004 (Figure 3-11), reflecting substantial growth in sales of light-duty trucks—in particular, growth in the market share of sport utility vehicles—relative to passenger cars (Figure 3-12). New vehicle fuel economy improved beginning in 2005, largely due to higher light-duty truck fuel economy standards, which have risen each year since 2005. The overall increase in fuel economy is also due to a slightly lower light-duty truck market share, which peaked in 2004 at 52 percent and declined to 48 percent in 2007.

Medium- and heavy-duty truck[11] CO_2 emissions increased by 79 percent (179.9 Tg CO_2 Eq.) from 1990 to 2007, representing the largest percentage increase of any major transportation mode. This increase was largely due to a substantial increase in truck freight movement, as medium- and heavy-duty truck VMT increased by 55 percent. Carbon dioxide from the domestic operation of commercial aircraft increased by 13 percent (18.2 Tg CO_2 Eq.) from 1990 to 2007, well below the growth in travel activity. The operational efficiency of commercial aircraft improved substantially because of a growing percentage of seats occupied per flight, improvements in the fuel efficiency of new aircraft, and the accelerated retirement of older, less fuel efficient aircraft. Across all categories of aviation,[12] CO_2 emissions increased by 5.1 percent (9.0 Tg CO_2 Eq.) between 1990 and 2007. This overall increase includes a 57 percent (18.6 Tg CO_2 Eq.) decrease in emissions from domestic military operations. For further information on all greenhouse gas emissions from transportation sources, please refer to Annex 3.2.

Figure 3-11

Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2007

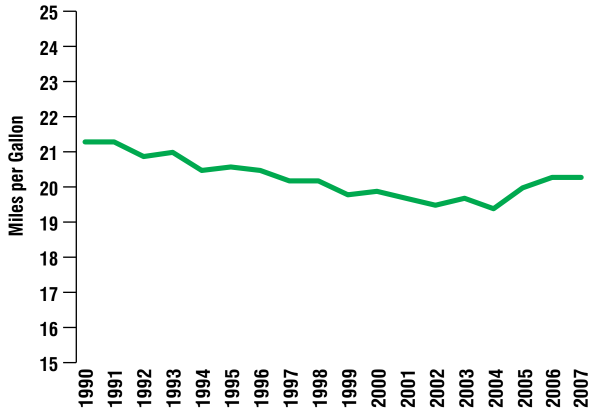
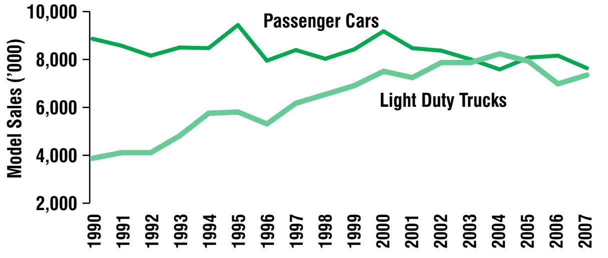


Figure 3-12

Sales of New Passenger Cars and Light-Duty Trucks, 1990–2007



Fossil Fuel Combustion CH_4 and N_2O Emissions from Mobile Sources

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. Inventory with the exception of pipelines, which are stationary; 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.). Annex 3.2 includes a

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[11] Includes "medium- and heavy-duty trucks" fueled by gasoline, diesel and LPG.

[12] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not accounted for in national emission totals.

Table 3-13: CH_4 Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel/Vehicle Type[a]	1990	1995	2000	2005	2006	2007
Gasoline On-Road	**4.2**	**3.8**	**2.8**	**1.9**	**1.7**	**1.6**
Passenger Cars	2.6	2.1	1.6	1.1	1.0	0.9
Light-Duty Trucks	1.4	1.4	1.1	0.7	0.6	0.6
Medium- and Heavy-Duty Trucks and Buses	0.2	0.2	0.1	0.1	0.1	0.1
Motorcycles	+	+	+	+	+	+
Diesel On-Road	**+**	**+**	**+**	**+**	**+**	**+**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**+**	**+**	**0.1**	**0.1**	**0.1**
Non-Road	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**
Ships and Other Boats	0.1	0.1	0.1	0.1	0.1	0.1
Rail	0.1	0.1	0.1	0.1	0.1	0.1
Agricultural Equipment[b]	0.1	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[c]	+	0.1	0.1	0.1	0.1	0.1
Aircraft	0.2	0.1	0.2	0.2	0.1	0.1
Other[d]	0.1	0.1	0.1	0.1	0.1	0.1
Total	**4.7**	**4.3**	**3.4**	**2.5**	**2.4**	**2.3**

+ Less than 0.05 Tg CO_2 Eq.

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

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

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

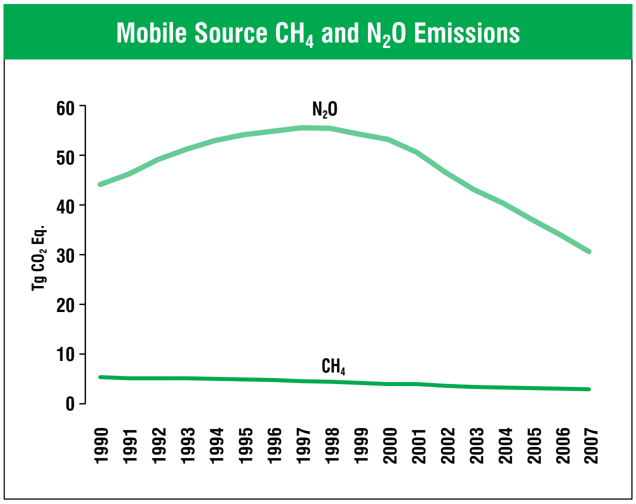
[d] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Note: Totals may not sum due to independent rounding.

summary of all emissions from both transportation and mobile sources. Table 3-13 and Table 3-14 provide CH_4 and N_2O emission estimates in Tg CO_2 Eq.[13]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.4 percent) but was the second largest source of U.S. N_2O emissions (10 percent). From 1990 to 2007, mobile source CH_4 emissions declined by 52 percent, to 2.3 Tg CO_2 Eq. (109 Gg), due largely to control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 31 percent, to 30.1 Tg CO_2 Eq. (97 Gg). Earlier generation control technologies initially resulted in higher N_2O emissions, causing a 26 percent increase in N_2O emissions from mobile sources between 1990 and 1998. Improvements in later-generation emission control technologies have reduced N_2O output, resulting in a 45 percent decrease in mobile source N_2O emissions from 1998 to 2007 (Figure 3-13). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks.

Figure 3-13


Mobile Source CH_4 and N_2O Emissions

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[13] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2007.

Table 3-14: N_2O Emissions from Mobile Combustion (Tg CO_2 Eq.)

Fuel/Vehicle Type[a]	1990	1995	2000	2005	2006	2007
Gasoline On-Road	**40.1**	**49.8**	**48.4**	**32.1**	**29.0**	**25.5**
Passenger Cars	25.4	26.9	25.2	17.7	15.7	13.7
Light-Duty Trucks	14.1	22.1	22.4	13.6	12.5	11.1
Medium- and Heavy-Duty Trucks and Buses	0.6	0.7	0.9	0.8	0.7	0.7
Motorcycles	+	+	+	+	+	+
Diesel On-Road	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Passenger Cars	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks and Buses	0.2	0.2	0.3	0.3	0.3	0.3
Alternative Fuel On-Road	**0.1**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Non-Road	**3.4**	**3.6**	**4.0**	**4.1**	**4.1**	**4.1**
Ships and Other Boats	0.4	0.4	0.5	0.4	0.4	0.4
Rail	0.3	0.3	0.3	0.4	0.4	0.4
Agricultural Equipment[b]	0.2	0.3	0.3	0.4	0.4	0.4
Construction/Mining Equipment[c]	0.3	0.4	0.4	0.5	0.5	0.5
Aircraft	1.7	1.7	1.9	1.9	1.8	1.8
Other[d]	0.4	0.5	0.5	0.6	0.6	0.6
Total	**43.7**	**53.7**	**52.8**	**36.7**	**33.5**	**30.1**

+ Less than 0.05 Tg CO_2 Eq.

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

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

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

[d] "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.

Note: Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology

The methodology used by the United States for estimating CO_2 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 (IPCC 2006). 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 Energy Information Administration (EIA) of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* and published supplemental tables on petroleum product detail (EIA 2008b). The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from Grillot (2008).[14]

   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

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[14] 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 emissions of 51 Tg CO_2 Eq. in 2007.

basis (every 4 years). These consumption data sets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[15]

It is also important to 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).[16]

2. *Subtract uses accounted for in the Industrial Processes 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 chapter, as they were consumed during non-energy related industrial activity. To make these adjustments, additional data were collected from AISI (1995 through 2008), CVR Energy (2008), Corathers (2008), U.S. Census Bureau (2008), EIA (2008g), EIA (2001), Smith, G. (2007), USGS (2008), USGS (1995, 1998, 2000 through 2002), USGS (1995), USGS (1991a through 2007a), USGS (1991b through 2007b), USGS (1991 through 2005), and USGS (1995 through 2006).[17]

3. *Adjust for biofuels, conversion of fossil fuels, and exports of CO_2.* Fossil fuel consumption estimates are adjusted downward to exclude (1) fuels with biogenic origins, (2) fuels created from other fossil fuels, and (3) exports of CO_2. Fuels with biogenic origins are assumed to result in no net CO_2 emissions, and must be subtracted from fuel consumption estimates. These fuels include ethanol added to motor gasoline and biomass gas used as natural gas. 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.[18] Since October 2000, the Dakota Gasification Plant has been exporting CO_2 to Canada by pipeline. Since this CO_2 is not emitted to the atmosphere in the United States, energy used to produce this CO_2 is subtracted from energy consumption statistics. To make these adjustments, additional data for ethanol and biogas were collected from EIA (2008b) and data for synthetic natural gas were collected from EIA (2008e), and data for CO_2 exports were collected from the Dakota Gasification Company (2006), Fitzpatrick (2002), Erickson (2003), and EIA (2006).

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 the Federal Highway Administration's (FHWA) VMT 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 upward to match the value obtained from the bottom-up analysis based on VMT. As the total distillate consumption estimate from EIA is considered to be accurate at the national level, the distillate consumption totals for the residential, commercial, and industrial sectors were adjusted downward proportionately. Similarly, as the total motor gasoline consumption estimate is considered to be accurate at the national level, the motor gasoline consumption totals for commercial and industrial sectors were adjusted downward proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008), Benson (2002 through 2004), DOE (1993 through 2008), EIA (2008a), EIA (1991 through 2005), EPA (2006), and FHWA (1996 through 2008).

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

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[15] See IPCC Reference Approach for estimating CO_2 emissions from fossil fuel combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[16] 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.

[17] 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 chapter.

[18] These adjustments are explained in greater detail in Annex 2.1.

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 (2008b).

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).[19] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Energy Support Center (Defense Logistics Agency) of the U.S. Department of Defense (DoD) (DESC 2008) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was obtained from FAA (2006); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2008) for 1990 through 2001, and 2007, 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 later 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 CO_2. The C content coefficients used by the United States were obtained from EIA's *Emissions of Greenhouse Gases in the United States 2007* (EIA 2008c) and EIA's *Monthly Energy Review* and published supplemental tables on petroleum product detail EIA (EIA 2008b). They are presented in Annexes 2.1 and 2.2.

8. *Estimate CO_2 Emissions*. Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the 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.

- For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2008); for each vehicle category, the percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2008).
- For non-road vehicles, activity data were obtained from AAR (2008), APTA (2007 through 2008), BEA (1991 through 2008), Benson (2002 through 2004), DOE (1993 through 2008), DESC (2008), DOC (1991 through 2008), DOT (1991 through 2007), EIA (2008a), EIA (2008d), EIA (2007), EIA (2002), EIA (1991 through 2005), EPA (2006), FAA (2008), and Gaffney (2007).
- For jet fuel used by aircraft, CO_2 emissions were calculated directly based on reported consumption of fuel as reported by EIA, and allocated to commercial aircraft using flight-specific fuel consumption data from the Federal Aviation Administration's (FAA) System for assessing Aviation's Global Emission (SAGE) model.[20] Allocation to domestic general aviation was made using FAA Aerospace Forecast data, and allocation to domestic military uses was made using DoD data (see Annex 3.7)

Heat contents and densities were obtained from EIA (2008a) and USAF (1998).[21]

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[19] See International Bunker Fuels section in this chapter for a more detailed discussion.

[20] FAA's System for assessing Aviation's Global Emissions (SAGE) model develops aircraft fuel burn and emissions for all commercial flights globally in a given year. The SAGE model dynamically models aircraft performance, fuel burn, and emissions, and is based on actual flight-by-flight aircraft movements. See <http://www.faa.gov/about/office_org/headquarters_offices/aep/models/sage/>.

[21] For a more detailed description of the data sources used for the analysis of the transportation end-use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.7.

Box 3-2: Carbon Intensity of U.S. Energy Consumption

Fossil fuels are the dominant source of energy in the United States, and CO_2 is emitted as a product from their combustion. Useful energy, however, is generated in the United States from many other sources that do not emit CO_2 in the energy conversion process, such as renewable (i.e., hydropower, biofuels, geothermal, solar, and wind) and nuclear sources.[22]

Energy-related CO_2 emissions can be reduced by not only lowering total energy consumption (e.g., through conservation measures) 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 Tg CO_2 Eq./QBtu for natural gas to upwards of 95 Tg CO_2 Eq./QBtu for coal and petroleum coke.[23] 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. Other sources of energy, however, may be directly or indirectly C neutral (i.e., 0 Tg CO_2 Eq./Btu). Energy generated from nuclear and many renewable sources do not result in direct emissions of CO_2. Biofuels such as wood and ethanol are also considered to be C neutral; although these fuels do emit CO_2, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 concentrations if the biogenic C emitted is offset by the growth of new biomass.[24] 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 example, the C intensity for the residential sector does not include the energy from or emissions related to the consumption of electricity for lighting or wood for heat. 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 Tg CO_2 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 (Tg CO_2 Eq./QBtu)

Sector	1990	1995	2000	2005	2006	2007
Residential[a]	57.4	56.7	56.7	56.6	56.6	56.3
Commercial[a]	59.3	57.8	57.1	57.6	57.2	57.0
Industrial[a]	63.7	62.7	62.5	64.0	64.2	63.9
Transportation[a]	71.0	71.0	71.0	71.1	71.1	71.1
Electricity Generation[b]	86.7	86.0	85.6	85.0	84.6	84.0
U.S. Territories[c]	74.1	74.1	73.2	74.6	74.6	74.7
All Sectors[c]	**72.7**	**72.2**	**72.7**	**73.1**	**73.1**	**72.8**

[a] Does not include electricity or renewable energy consumption.
[b] Does not include electricity produced using nuclear or renewable energy.
[c] Does not include nuclear or renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption.

In contrast to Table 3-15, Table 3-16 presents C intensity values that incorporate energy consumed from all sources (i.e., fossil fuels, renewables, and nuclear). In addition, the emissions related to the generation of electricity have been attributed to both electricity generation and the end-use sectors in which that electricity was eventually consumed.[25] This table, therefore, provides a more complete picture of

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[22] Small quantities of CO_2, however, are released from some geologic formations tapped for geothermal energy. These emissions are included with fossil fuel combustion emissions from the electricity generation. Carbon dioxide emissions may also be generated from upstream activities (e.g., manufacture of the equipment) associated with fossil fuel and renewable energy activities, but are not accounted for here.

[23] One exajoule (EJ) is equal to 10^{18} joules or 0.9478 QBtu.

[24] Net carbon fluxes from changes in biogenic carbon reservoirs in wooded or croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[25] In other words, the emissions from the generation of electricity are intentionally double counted by attributing them both to electricity generation and the end-use sector in which electricity consumption occurred.

Box 3-2: Carbon Intensity of U.S. Energy Consumption (continued)

the actual C intensity of each end-use sector per unit of energy consumed. The transportation end-use sector in Table 3-16 emerges as the most C intensive when all sources of energy are included, due to its almost complete reliance on petroleum products and relatively minor amount of biomass-based fuels used, such as ethanol. The “other end-use sectors” (i.e., residential, commercial, and industrial) use significant quantities of biofuels such as wood, thereby lowering the overall C intensity. The C intensity of the electricity generation sector differs greatly from the scenario in Table 3-15, where only the energy consumed from the direct combustion of fossil fuels was included. This difference is due almost entirely to the inclusion of electricity generation from nuclear and hydropower sources, which do not emit CO_2.

Table 3-16: Carbon Intensity from All Energy Consumption by Sector (Tg CO_2 Eq./QBtu)

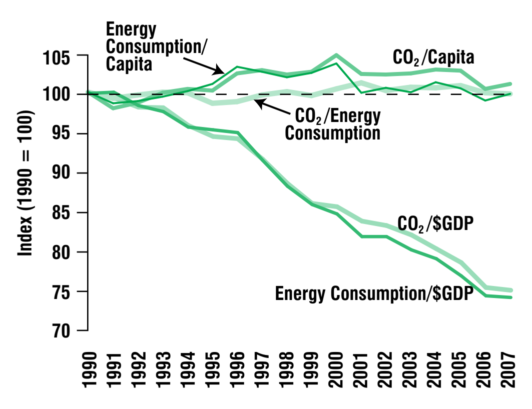
Sector	1990	1995	2000	2005	2006	2007
Transportation[a]	70.8	70.6	70.6	70.1	69.8	69.4
Other End-Use Sectors[a, b]	57.5	56.4	57.7	58.1	57.5	57.5
Electricity Generation[c]	59.0	57.9	59.9	59.9	58.9	59.3
All Sectors[d]	**61.1**	**60.3**	**61.4**	**61.6**	**61.1**	**61.0**

[a] Includes electricity (from fossil fuel, nuclear, and renewable sources) and direct renewable energy consumption.
[b] Other End-Use Sectors includes the residential, commercial, and industrial sectors.
[c] Includes electricity generation from nuclear and renewable sources.
[d] Includes nuclear and renewable energy consumption.
Note: Excludes non-energy fuel use emissions and consumption.

By comparing the values in Table 3-15 and Table 3-16, a few observations can be made. The use of renewable and nuclear energy sources has resulted in a significantly lower C intensity of the U.S. economy. Over the eighteen-year period of 1990 through 2007, however, the C intensity of U.S. energy consumption has been fairly constant, as the proportion of renewable and nuclear energy technologies have not changed significantly. Per capita energy consumption has fluctuated, but is now roughly equivalent to levels in 1990 (see Figure 3-14). Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2008).

Figure 3-14

U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990).

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 CO_2 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 for 2007. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report. These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with C emitted from Non-Energy Uses of Fossil Fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in 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 CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions. In particular, residual fuel consumption data for marine vessels are highly uncertain, as shown by the large fluctuations in emissions that do not mimic changes in other variables such as shipping ton miles.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 150 input variables were modeled for CO_2 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.[26] 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.[27]

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).[28] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo Sampling.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2007 were estimated to be between 5,622.3 and 6,029.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 6 percent above the 2007 emission estimate of 5,735.8 Tg CO_2 Eq.

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[26] 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.

[27] 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.

[28] 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 3-17: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-related Fossil Fuel Combustion by Fuel Type and Sector (Tg CO_2 Eq. and Percent)

Fuel/Sector	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg\ CO_2$ Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**2,086.5**	**2,015.7**	**2,284.1**	**-3%**	**+9%**
Residential	0.6	0.5	0.7	-6%	+15%
Commercial	6.8	6.4	7.8	-5%	+15%
Industrial	107.4	103.3	125.4	-4%	+17%
Transportation	NE	NE	NE	NA	NA
Electricity Generation	1,967.6	1,890.6	2,157.3	-4%	+10%
U.S. Territories	4.1	3.6	4.9	-12%	+19%
Natural Gas[b]	**1,216.5**	**1,226.2**	**1,295.9**	**+1%**	**+7%**
Residential	256.9	249.7	275.0	-3%	+7%
Commercial	163.4	158.9	174.9	-3%	+7%
Industrial	385.6	396.1	436.0	+3%	+13%
Transportation	35.4	34.4	37.9	-3%	+7%
Electricity Generation	373.8	363.1	393.0	-3%	+5%
U.S. Territories	1.4	1.2	1.7	-12%	+17%
Petroleum[b]	**2,432.4**	**2,279.1**	**2,553.7**	**-6%**	**+5%**
Residential	83.2	78.8	87.4	-5%	+5%
Commercial	44.2	42.1	46.0	-5%	+4%
Industrial	352.5	306.4	411.5	-13%	+17%
Transportation	1,852.0	1,710.8	1,947.9	-8%	+5%
Electricity Generation	55.3	53.3	58.8	-4%	+6%
U.S. Territories	**45.3**	**41.8**	**50.4**	**-8%**	**+11%**
Total (excluding Geothermal)[b]	**5,735.4**	**5,621.9**	**6,028.9**	**-2%**	**+5%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Total (including Geothermal)[b,c]	**5,735.8**	**5,622.3**	**6,029.3**	**-2%**	**+6%**

NA (Not Applicable)
NE (Not Estimated)
[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.
[c] Geothermal emissions added for reporting purposes, but an uncertainty analysis was not performed for CO_2 emissions from geothermal production.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

A source-specific QA/QC plan for CO_2 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 CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

Recalculations Discussion

Estimates of CO_2 from the industrial sector have been revised for the years 1990 through 2006 to subtract non-energy related consumption of coal, distillate fuel, and natural gas used in iron and steel and metallurgical coke production. A discussion of the methodology used to estimate non-energy related consumption is contained in the Iron and Steel Production and Metallurgical Coke Production section of the Industrial Processes chapter. In addition, the Energy Information Administration (EIA 2008b) updated energy consumption data for all years.

These revisions primarily impacted the emission estimates for 2006. Overall, these changes resulted in an average annual decrease of 17 Tg CO_2 Eq. (0.3 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2006.

Planned Improvements

An analysis is being undertaken to update the carbon content factors for fossil fuels, as presented in the annexes of this report. To reduce uncertainty of CO_2 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 CO_2 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.

CH_4 and N_2O from Stationary Combustion

Methodology

CH_4 and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type). National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, electricity generation, and U.S. territories. For the CH_4 and N_2O estimates, fuel consumption data for coal, natural gas, and fuel oil for the United States were obtained from EIA's *Monthly Energy Review* and unpublished supplemental tables on petroleum product detail (EIA 2008a). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2008b). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by Grillot (2008).[29] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[30] Construction and agricultural fuel use was obtained from EPA (2006). 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.

Emission factors for the four 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.

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

CH_4 emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. A total of 115 input variables were simulated for the uncertainty analysis of this source category (85 from the CO_2 emissions from fossil fuel combustion inventory estimation model and 30 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/

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[29] U.S. territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. territories are only included in the stationary combustion totals.

[30] 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.

EIA (2001) report.[31] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[32] However, the CH_4 emission factors differ from those used by EIA. Since these factors were obtained from IPCC/UNEP/OECD/IEA (1997), uncertainty ranges were assigned based on IPCC default uncertainty estimates (IPCC 2000).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-18. Stationary combustion CH_4 emissions in 2007 (including biomass) were estimated to be between 4.3 and 15.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 34 percent below to 128 percent above the 2007 emission estimate of 6.6 Tg CO_2 Eq.[33] Stationary combustion N_2O emissions in 2007 (including biomass) were estimated to be between 11.2 and 42.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 187 percent above the 2007 emissions estimate of 14.7 Tg CO_2 Eq.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

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 CH_4, N_2O, and

Table 3-18: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	6.6	4.3	15.1	-34%	+128%
Stationary Combustion	N_2O	14.7	11.2	42.1	-24%	+187%

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

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[31] 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.

[32] 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.

[33] 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.

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

Historical CH_4 and N_2O emissions from stationary sources (excluding CO_2) were revised due to a couple of changes. Slight changes to emission estimates for sectors are due to revised data from EIA (2008a). This revision is explained in greater detail in the section on CO_2 Emissions from Fossil Fuel Combustion within this sector. Wood consumption data from EIA (2008b) were revised for the residential, industrial, and electric power sectors. The combination of the methodological and historical data changes resulted in an average annual increase of less than 0.1 Tg CO_2 Eq. (less than 0.1 percent) in CH_4 emissions from stationary combustion and an average annual decrease of less than 0.1 Tg CO_2 Eq. (0.2 percent) in N_2O emissions from stationary combustion for the period 1990 through 2006.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty. Efforts will be made 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.

CH_4 and N_2O from Mobile Combustion

Methodology

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs)[34] are based on VMT and emission factors by vehicle and fuel type.

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 GHGs 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 emission 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 CO_2, CO, HC, NO_x, and PM from vehicles under various conditions, to approximate average driving characteristics.[35]

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[34] 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.

[35] Additional information regarding the model can be found online at http://www.epa.gov/OMS/m6.htm.

Emission factors for AFVs were 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 2007 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in *Highway Statistics* (FHWA 1996 through 2008). VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2008) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2008). VMT for AFVs were taken from Browning (2003). The age distributions of the U.S. vehicle fleet were obtained from EPA (2007c, 2000), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2000).

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 (1993, 1994a, 1994b, 1998, 1999a) and IPCC/UNEP/OECD/IEA (1997).

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 N_2O and CH_4 per kilogram of fuel consumed).[36] Activity data were obtained from AAR (2008), APTA (2007 through 2008), APTA (2006), BEA (1991 through 2005), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2008), DOE (1993 through 2008), DESC (2008), DOT (1991 through 2008), EIA (2008b, 2007a, 2007b, 2002), EIA (2007 through 2008), EIA (1991 through 2007), EPA (2006b), Esser (2003 through 2004), FAA (2008 and 2006), Gaffney (2007), and Whorton (2006 through 2007). Emission factors for non-road modes were taken from IPCC/UNEP/OECD/IEA (1997).

Uncertainty

A quantitative uncertainty analysis was conducted for the on-road portion of the mobile source sector using the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo simulation technique, using @ RISK software. The uncertainty analysis was performed on 2007 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following two major sets of input variables: (1) vehicle miles traveled (VMT) data, by vehicle and fuel type and (2) emission factor data, by vehicle, fuel, and control technology 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. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors, because emissions of these gases are not regulated in the United States (and, therefore, there are not adequate emission test data), and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

The results of the Tier 2 quantitative uncertainty analysis for the mobile source CH_4 and N_2O emissions from on-road vehicles are summarized in Table 3-19. As noted above, an uncertainty analysis was not performed for CH_4 and N_2O emissions from non-road vehicles. Mobile combustion CH_4 emissions (from on-road vehicles) in 2007 were estimated to be between 1.5 and 1.8 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 8 percent above the corresponding 2007 emission estimate of 1.7 Tg CO_2 Eq. Also at a 95 percent confidence level, mobile combustion N_2O emissions from on-road vehicles in 2007 were estimated to be between 21.1 and 30.8 Tg CO_2 Eq.,

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[36] 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 3-19: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Combustion ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a, b] ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Combustion	CH_4	1.7	1.5	1.8	-8%	+8%
Mobile Combustion	N_2O	26.0	21.1	30.8	-19%	+19%

[a] 2007 Emission estimates and the uncertainty range presented in this table correspond to on-road vehicles, comprising conventional and alternative fuel vehicles. Because the uncertainty associated with the emissions from non-road vehicles were not estimated, they were excluded in the estimates reported in this table.

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

indicating a range of 19 percent below to 19 percent above the corresponding 2007 emission estimate of 26.0 Tg CO_2 Eq.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Tier 2 approach to 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 CH_4 and N_2O please refer to the Uncertainty Annex.

QA/QC and Verification

A source-specific QA/QC 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

In order to ensure that these estimates are continuously improved, the calculation methodology is revised annually based on comments from internal and external reviewers. A number of adjustments were made to the methodologies used in calculating emissions in the current Inventory relative to the previous Inventory report.

New estimates of VMT by alternative fueled vehicles are now calculated using an updated method. The original VMT for alternative fuels was determined from energy use data obtained from EIA and projected. The new update uses actual energy use for 2005 through 2007 and improved estimations for future years.

Several changes were also made in the calculation of emissions from non-road vehicles. Commercial aircraft activity data for 1990 through 1999 is now calculated as the result of estimating DOT (1991 through 2008) data based upon the average difference between FAA (2006) and DOT (1991 through 2008) datasets for the years 2000 through 2005. For 2006 and 2007 commercial aircraft activity data, DOT (1991 through 2008) data is multiplied by the percentage difference between 2005 (the most recent available SAGE datapoint) and the respective year.

International jet fuel bunkers are now calculated by assigning the difference between the sum of domestic activity data (in TBtu) and the EIA transportation jet fuel allotment to the jet fuel bunkers category. Previously, international jet fuel bunkers were calculated based upon DOT (1991 through 2008) and BEA (1991 through 2005) data for the years 1990 through 1999 and 2006 through 2007 and estimated by FAA (2006) for 2000 through 2005.

Categories of non-road sources for which activity data are supplied from EPA's NONROAD model (EPA 2006) now include all Source Classification Codes available within the model, rather than a subset of all sources. This change results in an increase in emissions estimates from farm equipment, construction equipment, and other non-road sources.

As a result of these changes, average estimates of CH_4 and N_2O emissions from mobile combustion were slightly higher relative to the previous Inventory—showing an increase of no more than 2.5 percent in a given year—for the period 1990 through 2007. The greatest increase in absolute terms, 0.48 Tg CO_2 Eq. (1.4 percent), occurs with the 2006 N_2O estimate.

Planned Improvements

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

1. Develop updated emissions factors for diesel vehicles, motorcycles, and biodiesel vehicles. Previous emission factors were based upon extrapolations from other vehicle classes and new test data from Environment Canada will allow for better estimation of emission factors for these vehicles.
2. Develop updated emissions factors for ships and boats. Prior emission factors were derived from AP-42 for combustion of diesel and residual fuel. The new factors will take into account new data obtained from the Swedish Methodology for Environmental Data.
3. Develop new emission factors for non-road equipment. The current Inventory estimates for non-CO_2 emissions from non-road sources are based on emission factors from IPCC guidelines published in 1996. Recent data on non-road sources from Environment Canada and the California Air Resources Board will be investigated in order to assess the feasibility of developing new N_2O and CH_4 emissions factors for non-road equipment.
4. Examine the feasibility of estimating aircraft N_2O and CH_4 emissions by the number of takeoffs and landings, instead of total fuel consumption. Various studies have indicated that aircraft N_2O and CH_4 emissions are more dependent on aircraft takeoffs and landings than on total aircraft fuel consumption; however, aircraft emissions are currently estimated from fuel consumption data. FAA's SAGE database contains detailed data on takeoffs and landings for each calendar year starting in 1999, and could potentially be used to conduct a Tier II analysis of aircraft emissions. This methodology will require a detailed analysis of the number of takeoffs and landings by aircraft type on domestic trips and development of procedures to develop comparable estimates for years prior to 1999. The feasibility of this approach will be explored.
5. Develop improved estimates of domestic waterborne fuel consumption. The Inventory estimates for residual fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. The Department of Homeland Security (DHS) maintains an electronic reporting system that automatically registers monthly sales of bunker fuel at ports, which should provide a more accurate and comprehensive estimate of residual bunker fuel use by reducing the amount of non-reporting. This system has been used to collect data since 2002, and these data could be incorporated into the development of inventory figures. The DHS figures will need to be reconciled with figures from the current sources of data and a methodology will need to be developed to produce updated estimates for prior years.
6. 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. As MOVES goes through additional testing and refinement, 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 coke (manufactured from coking coal). The non-energy applications are equally diverse, and include 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).

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 63 percent of the total C consumed for non-energy purposes was stored in products, and not released to the atmosphere; the remaining 37 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of the Inventory. For example, some of the NEU products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Municipal Solid Waste Combustion source category. In addition, there is some overlap between fossil fuels consumed for non-energy uses and the fossil-derived CO_2 emissions accounted for in the Industrial Processes 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 these affect the mass of C in non-energy applications.

As shown in Table 3-20, fossil fuel emissions in 2007 from the non-energy uses of fossil fuels were 133.9 Tg CO_2 Eq., which constituted approximately 2 percent of overall fossil fuel emissions. In 2007, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,219.2 TBtu, an increase of 16 percent since 1990 (see Table 3-21). About 62.0 Tg of the C (227.2 Tg CO_2 Eq.) in these fuels was stored, while the remaining 36.5 Tg C (133.9 Tg CO_2 Eq.) was emitted. The proportion of C emitted as CO_2 has remained about constant since 1990, at about 37 to 40 percent of total non-energy consumption (see Table 3-20).

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 (2007) (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 3-21 and Table

Table 3-20: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (Tg CO_2 Eq.)

Type	1990	1995	2000	2005	2006	2007
Potential Emissions	312.8	350.4	387.7	375.9	383.4	361.1
C Stored	195.8	213.0	243.2	237.8	238.3	227.2
Emissions as a % of Potential	37%	39%	37%	37%	38%	37%
Emissions	**117.0**	**137.5**	**144.5**	**138.1**	**145.1**	**133.9**

Table 3-21: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Sector/Fuel Type	1990	1995	2000	2005	2006	2007
Industry	**4,222.3**	**4,804.4**	**5,278.9**	**5,153.4**	**5,245.8**	**4,966.4**
Industrial Coking Coal	+	75.0	82.2	53.3	74.7	33.0
Industrial Other Coal	8.2	11.3	12.4	11.9	12.4	12.4
Natural Gas to Chemical Plants, Other Uses	276.0	330.4	420.7	390.0	403.2	396.0
Asphalt & Road Oil	1,170.2	1,178.2	1,275.7	1,323.2	1,261.2	1,197.0
LPG	1,119.0	1,484.7	1,603.1	1,440.9	1,492.0	1,483.2
Lubricants	186.3	177.8	189.9	160.2	156.1	161.0
Pentanes Plus	77.3	285.3	228.5	145.9	105.7	132.4
Naphtha (<401° F)	325.7	350.6	592.3	678.2	619.4	543.3
Other Oil (>401° F)	677.2	612.7	553.8	518.3	572.9	511.7
Still Gas	21.3	40.1	12.6	67.7	123.9	88.4
Petroleum Coke	82.1	45.5	49.4	147.2	181.5	165.4
Special Naphtha	100.9	66.9	94.3	60.8	69.1	75.6
Distillate Fuel Oil	7.0	8.0	11.7	11.7	11.7	11.7
Waxes	33.3	40.6	33.1	31.4	26.1	21.9
Miscellaneous Products	137.8	97.1	119.2	112.8	136.0	133.5
Transportation	**176.0**	**167.9**	**179.4**	**151.3**	**147.4**	**152.0**
Lubricants	176.0	167.9	179.4	151.3	147.4	152.0
U.S. Territories	**86.7**	**90.8**	**165.5**	**107.7**	**110.3**	**100.9**
Lubricants	0.7	2.0	16.4	5.2	5.4	4.9
Other Petroleum (Misc. Prod.)	86.0	88.8	149.1	102.4	105.0	96.0
Total	**4,485.0**	**5,063.1**	**5,623.7**	**5,412.4**	**5,503.6**	**5,219.2**

+ Less than 0.05 TBtu.
Note: To avoid double-counting, coal coke, petroleum coke, natural gas consumption, and other oils are adjusted for industrial process consumption reported in the Industrial Processes sector. Natural gas, LPG, Pentanes Plus, Naphthas, Special Naphtha, and Other Oils are adjusted to account for exports of chemical intermediates derived from these fuels. For residual oil (not shown in the table), all non-energy use is assumed to be consumed in C black production, which is also reported in the Industrial Processes chapter.
Note: Totals may not sum due to independent rounding.

3-22 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes chapter.[37] Consumption values were also adjusted to subtract 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 this 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/UNEP/OECD/IEA (1997), 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.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-20). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

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[37] 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.

Table 3-22: 2007 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (Tg C/QBtu)	Potential Carbon (Tg C)	Storage Factor	Carbon Stored (Tg C)	Carbon Emissions (Tg C)	Carbon Emissions (Tg CO_2 Eq.)
Industry	**4,966.4**	–	**93.4**	–	**61.5**	**31.9**	**117.0**
Industrial Coking Coal	33.0	31.00	1.0	0.10	0.1	0.9	3.4
Industrial Other Coal	12.4	25.63	0.3	0.61	0.2	0.1	0.4
Natural Gas to Chemical Plants	396.0	14.47	5.7	0.61	3.5	2.2	8.1
Asphalt & Road Oil	1,197.0	20.62	24.7	1.00	24.7	+	+
LPG	1,483.2	16.76	24.9	0.61	15.3	9.6	35.2
Lubricants	161.0	20.24	3.3	0.09	0.3	3.0	10.8
Pentanes Plus	132.4	18.24	2.4	0.61	1.5	0.9	3.4
Naphtha (<401° F)	543.3	18.14	9.9	0.61	6.0	3.8	14.0
Other Oil (>401° F)	511.7	19.95	10.2	0.61	6.3	3.9	14.5
Still Gas	88.4	17.51	1.5	0.61	1.0	0.6	2.2
Petroleum Coke	165.4	27.85	4.6	0.30	1.4	3.2	11.8
Special Naphtha	75.6	19.86	1.5	0.61	0.9	0.6	2.1
Distillate Fuel Oil	11.7	19.95	0.2	0.50	0.1	0.1	0.4
Waxes	21.9	19.81	0.4	0.58	0.3	0.2	0.7
Miscellaneous Products	133.5	20.33	2.7	0.00	0.0	2.7	9.9
Transportation	**152.0**	–	**3.1**	–	**0.3**	**2.8**	**10.2**
Lubricants	152.0	20.24	3.1	0.09	0.3	2.8	10.2
U.S. Territories	**100.9**	–	**2.0**	–	**0.2**	**1.8**	**6.7**
Lubricants	4.9	20.24	0.1	0.09	0.0	0.1	0.3
Other Petroleum (Misc. Prod.)	96.0	20.00	1.9	0.10	0.2	1.73	6.3
Total	**5,219.2**		**98.5**		**62.0**	**36.5**	**133.9**

\+ Less than 0.05 TBtu.

\- Not applicable.

[a] To avoid double counting, exports have been deducted.

Note: Totals may not sum due to independent rounding.

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 volatile organic compound, solvent, and non-combustion CO emissions, *Toxics Release Inventory* (TRI) releases, hazardous waste incineration, and energy recovery. 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 1995, 2001), National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data (EPA 2008), *Toxics Release Inventory, 1998* (2000a), *Biennial Reporting System* (EPA 2004a, 2006b, 2007), and pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005); the National Petrochemical & Refiners Association (NPRA 2001); the National Asphalt Pavement Association (Connolly 2000); the Emissions Inventory Improvement Program (EIIP 1998, 1999); the U.S. Census Bureau (1999, 2003, 2004); the American Plastics Council (APC 2000, 2001, 2003, 2005, 2006; Eldredge-Roebuck 2000); the Society of the Plastics Industry (SPI 2000); Bank of Canada (2006); Financial Planning Association (2006); INEGI (2006); Statistics Canada (2006); the United States International Trade Commission (2006 through 2008); the Pesticide Action Network (PAN 2002); Gosselin, Smith, and Hodge (1984); the Rubber Manufacturers' Association (RMA 2002, 2006; STMC 2003); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005 through 2007); the *Material Safety Data Sheets* (Miller 1999); the Chemical Manufacturer's Association

(CMA 1999); and the American Chemistry Council (ACC 2005 through 2008) Specific data sources are listed in full detail in Annex 2.3.

Uncertainty

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 Tier 2 methodology (Monte Carlo 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), the storage factors were taken directly from the IPCC Guidelines for National Greenhouse Gas Inventories, 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 Tier 2 quantitative uncertainty analysis are summarized in Table 3-23 (emissions) and Table 3-24 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2007 was estimated to be between 107.0 and 144.6 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below to 8 percent above the 2007 emission estimate of 133.9 Tg CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

In Table 3-24, feedstocks and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—appears to have tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

QA/QC and Verification

A source-specific QA/QC 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 2007 as well as their trends across the time series.

Table 3-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	79.9	64.4	95.9	-19%	+20%
Asphalt	CO_2	0.0	0.2	0.8	NA	NA
Lubricants	CO_2	21.4	17.7	24.9	-17%	+16%
Waxes	CO_2	0.7	0.5	1.1	-24%	+64%
Other	CO_2	31.9	13.7	33.0	-57%	+3%
Total	**CO_2**	**133.9**	**107.0**	**144.6**	**-20%**	**+8%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
NA (Not Applicable)

Table 3-24: Tier 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2007 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	61%	59%	63%	-4%	+3%
Asphalt	CO_2	100%	99%	100%	-1%	+0%
Lubricants	CO_2	9%	4%	17%	-57%	+89%
Waxes	CO_2	58%	44%	70%	-25%	+20%
Other	CO_2	17%	17%	64%	+2%	+273%

[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).

Recalculations Discussion

Non-energy end uses for petroleum coke (other than in the industrial processing sectors, where it is accounted for separately) had not been identified in the past. Huurman (2006) suggests that in the Netherlands petroleum coke is used in some pigments, and identifies its corresponding storage factor as 0.3. This year, it was assumed that petroleum coke used for non-energy purposes (and not accounted for in the Industrial Processes chapter, viz., for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, ammonia, urea, and ferroalloys) is used in pigments, with a storage factor of 0.3 (rather than the value of 0.5 used previously). This resulted in an average 1.4% increase in NEU emissions across the time series.

Planned Improvements

There are several improvements planned for the future:

- Future updates in line with the 2006 IPCC Guidelines. These changes could affect both the non-energy use and industrial processes sections.
- 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).

Finally, 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 and 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 conducting analyses of C fate similar to those described in Annex 2.3.

3.3. Coal Mining (IPCC Source Category 1B1a)

Three types of coal mining related activities release CH_4 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. Underground coal mines contribute the largest share of CH_4 emissions. In 2007, 233 coal mines, (including all 131 gassy underground coal mines), in the United States employ ventilation systems to ensure that CH_4 levels remain within safe concentrations. These systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Additionally, 20 U.S. coal mines supplement ventilation systems with degasification systems. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large volumes of CH_4 before, during, or after mining. In 2007, 15 coal mines collected CH_4 from degasification systems and utilized this gas, thus reducing emissions to the atmosphere. Of these mines, 13 coal mines sold CH_4 to the natural gas pipeline, one coal mine generated electricity, and one coal mine used CH_4 from its degasification system to heat mine ventilation air on site. On addition, one of the coal mines that sold gas to pipelines also used CH_4 to fuel a thermal coal dryer. Surface coal mines also release CH_4 as the overburden is removed and the coal is exposed, but the level of emissions is much lower than from underground mines. Finally, some of the CH_4 retained in the coal after mining is released during processing, storage, and transport of the coal.

Total CH_4 emissions in 2007 were estimated to be 57.6 Tg CO_2 Eq. (2,744 Gg), a decline of 31 percent since 1990 (see Table 3-25 and Table 3-26). Of this amount,

Table 3-25: CH_4 Emissions from Coal Mining (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Underground Mining	62.3	46.8	39.5	35.2	35.8	35.5
Liberated	67.9	59.2	54.4	50.1	54.5	47.7
Recovered & Used	(5.6)	(12.4)	(14.9)	(14.9)	(18.6)	(12.3)
Surface Mining	12.0	11.5	12.3	13.3	14.0	13.8
Post-Mining (Underground)	7.7	6.9	6.7	6.4	6.3	6.1
Post-Mining (Surface)	2.0	1.9	2.0	2.2	2.3	2.2
Total	**84.1**	**67.1**	**60.5**	**57.1**	**58.4**	**57.6**

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

Table 3-26: CH_4 Emissions from Coal Mining (Gg)

Activity	1990	1995	2000	2005	2006	2007
Underground Mining	2,968	2,225	1,883	1,677	1,705	1,689
Liberated	3,234	2,817	2,593	2,387	2,593	2,273
Recovered & Used	(266)	(592)	(710)	(710)	(888)	(584)
Surface Mining	574	548	586	633	668	659
Post-Mining (Underground)	368	330	318	306	298	290
Post-Mining (Surface)	93	89	95	103	109	107
Total	**4,003**	**3,193**	**2,881**	**2,719**	**2,780**	**2,744**

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

underground mines accounted for 62 percent, surface mines accounted for 24 percent, and post-mining emissions accounted for 15 percent. The decline in CH_4 emissions from underground mines from 1996 to 2002 was the result of the reduction of overall coal production, the mining of less gassy coal, and an increase in CH_4 recovered and used. Since that time, underground coal production and the associated methane emissions have remained fairly level, while surface coal production and its associated emissions have generally increased.

Methodology

The methodology for estimating CH_4 emissions from coal mining consists of two parts. The first part involves estimating CH_4 emissions from underground mines. Because of the availability of ventilation system measurements, underground mine emissions can be estimated on a mine-by-mine basis and then summed to determine total emissions. The second step involves estimating emissions from surface mines and post-mining activities by multiplying basin-specific coal production by basin-specific emission factors.

Underground mines. Total CH_4 emitted from underground mines was estimated as the sum of CH_4 liberated from ventilation systems and CH_4 liberated by means of degasification systems, minus CH_4 recovered and used. The Mine Safety and Heath Administration (MSHA) samples CH_4 emissions from ventilation systems for all mines with detectable[38] CH_4 concentrations. These mine-by-mine measurements are used to estimate CH_4 emissions from ventilation systems.

Some of the higher-emitting underground mines also use degasification systems (e.g., wells or boreholes) that remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Various approaches were employed to estimate the quantity of CH_4 collected by each of the twenty mines using these systems, depending on available data. For example, some mines report to EPA the amount of CH_4 liberated from their degasification systems. For mines that sell recovered CH_4 to a pipeline, pipeline sales data published by state petroleum and natural gas agencies were used to estimate degasification emissions. For those mines for which no other data are available, default recovery efficiency values were developed, depending on the type of degasification system employed.

Finally, the amount of CH_4 recovered by degasification systems and then used (i.e., not vented) was estimated. In 2007, 13 active coal mines sold recovered CH_4 into the local gas pipeline networks, one used recovered CH_4 to generate electricity while one coal mine used recovered CH_4 on site for heating. Emissions avoided for these projects were estimated using gas sales data reported by various state agencies. For most mines with recovery systems, companies and state agencies provided individual well production information, which was used to assign gas sales to a particular year. For the few remaining mines, coal mine operators supplied information regarding the number of years in advance of mining that gas recovery occurs.

Surface Mines and Post-Mining Emissions. Surface mining and post-mining CH_4 emissions were estimated by multiplying basin-specific coal production, obtained from the Energy Information Administration's *Annual Coal Report* (see Table 3-27) (EIA 2006), by basin-specific emission factors. Surface mining emission factors were developed by assuming that surface mines emit two times as much CH_4 as the average in situ CH_4 content of the coal. Revised data on in situ CH_4 content and emissions factors are taken from EPA (2005), EPA (1996), and AAPG (1984). This calculation accounts for CH_4 released from the strata surrounding the coal seam. For post-mining emissions, the emission factor was assumed to be 32.5 percent of the average in situ CH_4 content of coals mined in the basin.

Table 3-27: Coal Production (Thousand Metric Tons)

Year	Underground	Surface	Total
1990	384,250	546,818	931,068
1995	359,477	577,638	937,115
2000	338,173	635,592	973,765
2005	334,404	691,460	1,025,864
2006	325,703	728,459	1,054,162
2007	319,145	720,035	1,039,179

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[38] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

Table 3-28: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Coal Mining (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	57.6	48.6	71.2	-16%	+24%

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

Uncertainty

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Tier 2 uncertainty estimation methodology. Because emission estimates from underground ventilation systems were based on actual measurement data, uncertainty is relatively low. A degree of imprecision was introduced because the measurements used were not continuous but rather an average of quarterly instantaneous readings. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky and Wang 2000). Estimates of CH_4 recovered by degasification systems are relatively certain because many coal mine operators provided information on individual well gas sales and mined through dates. Many of the recovery estimates use data on wells within 100 feet of a mined area. Uncertainty also 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 currently estimated.

Compared to underground mines, there is considerably more uncertainty associated with surface mining and post-mining emissions because of the difficulty in developing accurate emission factors from field measurements. However, since underground emissions comprise 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 Tier 2 quantitative uncertainty analysis are summarized in Table 3-28. Coal mining CH_4 emissions in 2007 were estimated to be between 48.6 and 71.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 16 percent below to 24 percent above the 2007 emission estimate of 57.6 Tg CO_2 Eq.

Recalculations Discussion

In 2007, calculations of emissions avoided at the four Jim Walters Resources (JWR) coal mines in Alabama were performed using the previous EPA method. This was done in order to take a better documented approach and to track the four coal mines individually rather than as a group. Emissions avoided calculations for any pre-drainage wells at JWR coal mines are based on publicly-available data records from the Alabama State Oil & Gas Board. Emission reductions are calculated for pre-drainage wells that are located inside the mine plan boundaries and are declared "shut-in" by the O&G Board. The total production for a well is claimed in the year that the well was shut-in and mined through.

3.4. Abandoned Underground Coal Mines (IPCC Source Category 1B1a)

Underground coal mines contribute the largest share of CH_4 emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, the CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or, if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Gross abandoned mine CH_4 emissions ranged from 6.0 to 9.1 Tg CO_2 Eq. from 1990 through 2007, varying, in general, by less than 1 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 (9.1 Tg CO_2 Eq.) due to the large number of mine closures from 1994 to 1996 (70 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. There were fewer than fifteen gassy mine closures during each of the years from 1998 through 2007, with only three closures in 2007. By 2007, gross abandoned mine emissions increased to 9.0 Tg CO_2 Eq. (see Table 3-29 and Table 3-30). Gross emissions are reduced by CH_4 recovered and used at 27 mines, resulting in net emissions in 2007 of 5.7 Tg CO_2 Eq.

Methodology

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, 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

Table 3-29: CH_4 Emissions from Abandoned Underground Coal Mines (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Abandoned Underground Mines	6.0	8.9	8.9	7.0	7.5	9.0
Recovered & Used	0.0	0.7	1.5	1.4	2.0	3.3
Total	**6.0**	**8.2**	**7.4**	**5.6**	**5.5**	**5.7**

Note: Totals may not sum due to independent rounding.

Table 3-30: CH_4 Emissions from Abandoned Underground Coal Mines (Gg)

Activity	1990	1995	2000	2005	2006	2007
Abandoned Underground Mines	288	424	422	334	359	428
Recovered & Used	0	32	72	68	96	155
Total	**288**	**392**	**350**	**265**	**263**	**273**

Note: Totals may not sum due to independent rounding.

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 CH_4 emissions over time for a given mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability and isotherm. As CH_4 leaves the system, the reservoir pressure, Pr, declines as described by the isotherm. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure, for a vented mine, and the PI term is essentially constant at the pressures of interest (atmospheric to 30 psia). 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:

$$q = q_i\,(1+bD_it)^{(-1/b)}$$

where,

q = Gas rate at time t in thousand cubic feet per day (mcfd)
q_i = Initial gas rate at time zero (t_o) in mcfd
b = The hyperbolic exponent, dimensionless
D_i = Initial decline rate, 1/yr
t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability and adsorption isotherms (EPA 2003).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emission 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 no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooding 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 2003).

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

where,

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

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the rate that would be emitted if the mine had an open vent. The total volume emitted will be the same, but will occur over a longer period. The methodology, therefore, treats the emissions prediction from a sealed mine similar to emissions from a vented mine, but uses a lower initial rate depending on the degree of sealing. The computational fluid dynamics simulator was again used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × [1 – (initial emissions from sealed mine / emission rate at abandonment prior to sealing)]. Significant differences are seen between 50 percent, 80 percent, and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2003).

For active coal mines, those mines producing over 100 mcfd account for 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that 448 abandoned mines closing after 1972 produced emissions greater than 100 mcfd when active. Further, the status of 267 of the 448 mines (or 60 percent) is known to be either: (1) vented to the atmosphere; (2) sealed to some degree (either earthen or concrete seals); or, (3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 40 percent of the mines were placed in one of the three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2003).

Inputs to the decline equation require the average emission rate and the date of abandonment. Generally this data is available for mines abandoned after 1972; 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 after 1971. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1972 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. 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 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 CH_4 emissions rates during the 1970s (EPA 2003).

Abandoned mines emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 mcfd at the time of abandonment; a list by region is shown in Table 3-31. 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. 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. Methane degasification amounts were added to the quantity of CH_4 ventilated for the total CH_4 liberation rate for fifteen mines that closed between 1992 and 2007. Since the sample of gassy mines (with active mine emissions greater than 100 mcfd) is assumed to account for 78 percent of the pre-1971 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 2007, emission totals were downwardly adjusted to reflect abandoned mine CH_4 emissions avoided from those mines. The inventory totals were not adjusted for abandoned mine reductions in 1990 through 1992, because no data was reported for abandoned coal mining CH_4 recovery projects during that time.

Uncertainty

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) CH_4 flow capacity as expressed by permeability; and (3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but values that represent the highest and lowest quartile of the cumulative probability density function of each parameter.

Table 3-31: Number of Gassy Abandoned Mines Occurring in U.S. Basins Grouped by Class According to Post-abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appalachia	24	25	48	97	115	212
Illinois	28	3	14	45	25	70
Northern Appalachia	42	22	16	79	32	112
Warrior Basin	0	0	15	15	0	15
Western Basins	25	3	2	30	9	39
Total	**119**	**53**	**95**	**267**	**181**	**448**

Table 3-32: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	5.7	4.6	7.1	-19%	+23%

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

Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-32. Abandoned coal mines CH_4 emissions in 2007 were estimated to be between 4.6 and 7.1 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 19 percent below to 23 percent above the 2007 emission estimate of 5.7 Tg CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is used in the methodology. The largest degree of uncertainty is associated with the unknown status mines (which account for 40 percent of the mines), with a ±53 percent uncertainty.

3.5. 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 104.7 Tg CO_2 Eq. (4,985 Gg) of CH_4 in 2007, a 19 percent decrease over 1990 emissions (see Table 3-33 and Table 3-34), and 28.7 Tg CO_2 Eq. (28,680 Gg) of non-combustion CO_2 in 2007, a 15 percent decrease over 1990 emissions (see Table 3-35 and Table 3-36). Improvements in management practices and

Table 3-33: CH_4 Emissions from Natural Gas Systems ($Tg\ CO_2$ Eq.)[a]

Stage	1990	1995	2000	2005	2006	2007
Field Production	34.2	38.7	40.3	26.4	27.8	22.4
Processing	15.0	15.1	14.5	11.6	11.6	12.3
Transmission and Storage	47.0	46.4	44.6	39.1	38.4	40.4
Distribution	33.4	32.4	31.4	29.3	27.0	29.6
Total	**129.6**	**132.6**	**130.8**	**106.3**	**104.8**	**104.7**

[a] Including CH_4 emission reductions achieved by the Natural Gas STAR program and NESHAP regulations.
Note: Totals may not sum due to independent rounding.

Table 3-34: CH_4 Emissions from Natural Gas Systems (Gg)[a]

Stage	1990	1995	2000	2005	2006	2007
Field Production	1,629	1,842	1,918	1,256	1,323	1,066
Processing	714	717	692	550	555	584
Transmission and Storage	2,237	2,212	2,123	1,862	1,828	1,926
Distribution	1,591	1,543	1,498	1,393	1,285	1,409
Total	**6,171**	**6,314**	**6,231**	**5,062**	**4,991**	**4,985**

[a] Including CH_4 emission reductions achieved by the Natural Gas STAR program and NESHAP regulations.
Note: Totals may not sum due to independent rounding.

Table 3-35: Non-combustion CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq.)

Stage	1990	1995	2000	2005	2006	2007
Field Production	5.9	9.1	6.0	7.6	8.2	7.4
Processing	27.8	24.6	23.3	21.7	21.2	21.2
Transmission and Storage	0.1	0.1	0.1	0.1	0.1	0.1
Distribution	+	+	+	+	+	+
Total	**33.7**	**33.8**	**29.4**	**29.5**	**29.5**	**28.7**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 3-36: Non-combustion CO_2 Emissions from Natural Gas Systems (Gg)

Stage	1990	1995	2000	2005	2006	2007
Field Production	5,877	9,084	5,956	7,625	8,235	7,389
Processing	27,752	24,621	23,332	21,736	21,204	21,189
Transmission and Storage	59	61	61	61	60	61
Distribution	46	45	44	41	40	41
Total	**33,733**	**33,810**	**29,394**	**29,463**	**29,540**	**28,680**

Note: Totals may not sum due to independent rounding.

technology, along with the replacement of older equipment, have helped to stabilize emissions. Methane emissions decreased since 2006 despite an increase in production and production wells due to a decrease in 73 offshore platforms and an increase of 25 percent in Natural Gas STAR production sector emissions reductions.

Methane and non-combustion CO_2 emissions from natural gas systems are generally process related, with normal operations, routine maintenance, and system upsets being the primary contributors. Emissions from normal operations include: natural gas engines and turbine uncombusted exhaust, bleed and discharge emissions from pneumatic devices, 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 CH_4 and non-combustion CO_2 emissions are discussed.

Field Production. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of CH_4 emissions. Flaring emissions account for the majority of the non-combustion CO_2 emissions. Emissions from field production accounted for approximately 21 percent of CH_4 emissions and about 26 percent of non-combustion CO_2 emissions from natural gas systems in 2007.

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 CH_4 emissions from compressors, including compressor seals, are the primary emission source from this stage. The majority of non-combustion CO_2 emissions come from acid gas removal units, which are designed to remove CO_2 from natural gas. Processing plants account for about 12 percent of CH_4 emissions and approximately 74 percent of non-combustion CO_2 emissions from natural gas systems.

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 United States transmission system. Fugitive CH_4 emissions from these compressor stations and from metering and regulating stations account for the majority of the emissions from this stage. Pneumatic devices and engine uncombusted exhaust are also sources of CH_4 emissions from transmission facilities.

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 these storage facilities. Methane emissions from the transmission and storage sector account for approximately 39 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage account for less than 1 percent of the non-combustion CO_2 emissions from natural gas systems.

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 over 1,190,000 miles of distribution mains in 2007, an increase from just over 944,000 miles in 1990 (OPS 2007b). Distribution system emissions, which account for approximately 28 percent of CH_4 emissions from natural gas systems and less than 1 percent of non-combustion CO_2 emissions, result mainly from fugitive emissions from gate stations and pipelines. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced emissions from this stage. Distribution system CH_4 emissions in 2007 were 11.4 percent lower than 1990 levels.

Methodology

The primary basis for estimates of CH_4 and non-combustion-related CO_2 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 CH_4 emission and activity factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. The same activity factors were used to estimate both CH_4 and non-combustion CO_2 emissions. However, the CH_4 emission factors were adjusted for CO_2 content when estimating fugitive and vented non-combustion CO_2 emissions. The EPA/GRI study was based on a combination of process engineering studies and measurements at representative gas facilities. From this analysis, a 1992 emission estimate was developed using the emission and activity factors, except where direct activity data was available (e.g., offshore platform counts, processing plant counts, transmission pipeline miles, and distribution pipelines). For other years, a set of industry activity factor drivers was developed that can be used to update activity factors. These 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. See Annex 3.4 for more detailed information on the methodology and data used to calculate CH_4 and non-combustion CO_2 emissions from natural gas systems.

Activity factor data were taken from the following sources: American Gas Association (AGA 1991–1998); Minerals and Management Service (MMS 2008a-d); *Monthly Energy Review* (EIA 2008f); *Natural Gas Liquids Reserves Report* (EIA 2005); *Natural Gas Monthly* (EIA 2008b,c,e); the Natural Gas STAR Program annual emissions savings (EPA 2008); *Oil and Gas Journal* (OGJ 1997–2008); Office of Pipeline Safety (OPS 2008a-b) and other Energy Information Administration publications (EIA 2001, 2004, 2008a,d); *World Oil Magazine* (2008a-b). Data for estimating emissions from hydrocarbon production tanks were incorporated (EPA 1999). Coalbed CH_4 well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2008) and the Alabama State Oil and Gas Board (Alabama 2008). Other state well data was taken from: American Association of Petroleum Geologists (AAPG 2004); Brookhaven College (Brookhaven 2004); Kansas Geological Survey (Kansas 2008); Montana Board of Oil and Gas Conservation (Montana 2008); Oklahoma Geological Survey (Oklahoma 2008); Morgan Stanley (Morgan Stanley 2005); Rocky Mountain Production Report (Lippman (2003); New Mexico Oil Conservation Division (New Mexico 2008a,b); Texas Railroad Commission (Texas 2008a-d); Utah Division of Oil, Gas and Mining (Utah 2008). Emission factors were taken from EPA/GRI (1996). GTI's Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. Additional information about CO_2 content in transmission-quality natural gas was obtained via the internet from numerous

U.S. transmission companies to help further develop the non-combustion CO_2 emission factors.

Uncertainty

A quantitative uncertainty analysis was conducted to determine the level of uncertainty surrounding estimates of emissions from natural gas systems. Performed using @RISK software and the IPCC-recommended Tier 2 methodology (Monte Carlo Simulation technique), this analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. The results presented below provide with 95 percent certainty the range within which emissions from this source category are likely to fall.

The heterogeneous nature of the natural gas industry makes it difficult to sample facilities that are completely representative of the entire industry. Because of this, scaling up from model facilities introduces a degree of uncertainty. Additionally, highly variable emission rates were measured among many system components, making the calculated average emission rates uncertain. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-37. Natural gas systems CH_4 emissions in 2007 were estimated to be between 79.7 and 150.2 Tg CO_2 Eq. at a 95 percent confidence level. Natural gas systems non-energy CO_2 emissions in 2007 were estimated to be between 21.8 and 41.1 Tg CO_2 Eq. at 95 percent confidence level.

Recalculations Discussion

In the previous Inventory, all activity factors were estimated using base year activity factors and activity drivers even if activity data was publicly available for all years in the time series. This was done to maintain consistency of methodology across all sources. However, this resulted in discrepancy in the activity factors in outer years. This is because activity data in the base year have been revised since the GRI activity factors were developed. Additionally, the oil and gas industry has undergone changes that do not get reflected in the outer years, if the base year activity factors are driving the entire time series.

Therefore, where direct activity data were available for activity factors, the activity factors were replaced with the direct data for all years to adapt the natural gas Inventory to publicly available data and adjust the current Inventory to better reflect emissions from these sources. Direct activity data are available for shallow water gas platforms, deep water gas platforms, gas processing plants, transmission pipeline miles, distribution mains pipeline miles (by pipeline material), and distribution services (by pipeline material). This substitution resulted in a 3.5 to 4 percent increase in CH_4 emissions in the inventory time series.

The second recalculation is a result of changing several base year (1992) activity factors to re-estimated EPA/GRI (1996). Methane Emissions from the Natural Gas Industry report base year activity factors. The GRI study consists of

Table 3-37: Tier 2 Quantitative Uncertainty Estimates for CH_4 and Non-energy CO_2 Emissions from Natural Gas Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound[c]	Upper Bound[c]	Lower Bound[c]	Upper Bound[c]
Natural Gas Systems	CH_4	104.7	79.7	150.2	-24%	+43%
Natural Gas Systems[b]	CO_2	28.7	21.8	41.1	-24%	+43%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] An uncertainty analysis for the non-energy CO_2 emissions was not performed. The relative uncertainty estimated (expressed as a percent) from the CH_4 uncertainty analysis was applied to the point estimate of non-energy CO_2 emissions.
[c] 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.

direct activity factors and derived activity factors. Direct activity factors refer to publicly available data, whereas derived activity factors were obtained by extrapolating sample data collected from the surveys to national estimates using direct factors such as gas production, gas throughput, etc. The base year derived activity factors were re-estimated by updating the 1992 direct activity factor with the publicly available data discussed in the previous paragraph.

All other recalculations are the result of updating the previous Inventory activity data with revised values.

Planned Improvements

Most of the activity factors and emission factors in the natural gas model are from the EPA/GRI (1996) study. A study is currently underway to review selected emission factors in the natural gas industry, and as appropriate, conduct measurement-based studies to develop updated emission factors to better reflect current national circumstances. Results from these studies are expected in the next few years, and will be incorporated into the Inventory, pending a peer review.

3.6. Petroleum Systems (IPCC Source Category 1B2a)

CH_4 emissions from petroleum systems are primarily associated with crude oil production, transportation, and refining operations. During each of these activities, CH_4 emissions are released to the atmosphere as fugitive emissions, vented emissions, emissions from operational upsets, and emissions from fuel combustion. Fugitive and vented CO_2 emissions from petroleum systems are primarily associated with crude oil production and are negligible in the transportation and refining operations. Combusted CO_2 emissions are already accounted for in the Fossil Fuels Combustion source category, and hence have not been taken into account in the Petroleum Systems source category. Total CH_4 and CO_2 emissions from petroleum systems in 2007 were 28.8 Tg CO_2 Eq. (1,370 Gg CH_4) and 0.3 Tg CO_2 (287 Gg), respectively. Since 1990, CH_4 emissions have declined by 15 percent, due to industry efforts to reduce emissions and a decline in domestic oil production (see Table 3-38 and Table 3-39). Carbon dioxide emissions have also declined by 24 percent since 1990 due to similar reasons (see Table 3-40 and Table 3-41).

Production Field Operations. Production field operations account for almost 98 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for 91.5 percent of the emissions from the production sector, unburned CH_4 combustion emissions account for 5.2 percent, fugitive emissions are 3.2 percent, and process upset emissions are slightly over two-tenths of a percent. The most dominant sources of emissions, in order of magnitude, are shallow water offshore oil platforms, natural-gas-powered pneumatic devices (low bleed and high bleed), field storage tanks, gas engines, chemical injection pumps and deep water offshore platforms. These seven sources alone emit over 95 percent of the production field operations emissions. Offshore platform emissions are a combination of fugitive, vented, and unburned fuel combustion emissions from all equipment housed on oil platforms producing oil and associated gas. Emissions from high and low-bleed pneumatics occur when pressurized gas that is used for control devices is bled to the atmosphere as they cycle open and closed to modulate the system. Emissions from storage tanks occur when the CH_4 entrained in crude oil under pressure volatilizes once the crude oil is put into storage tanks at atmospheric pressure. Emissions from gas engines are due to unburned CH_4 that vents with the exhaust. Emissions from chemical injection pumps are due to the 25 percent that use associated gas to drive pneumatic pumps. The remaining five percent of the emissions are distributed among 26 additional activities within the four categories: vented, fugitive, combustion and process upset emissions. For more detailed, source-level data on CH_4 emissions in production field operations, refer to Annex 3.5.

Vented CO_2 associated with natural gas emissions from field operations account for 99 percent of the total CO_2 emissions from this source category, while fugitive and process upsets together account for 1 percent of the emissions. The most dominant sources of vented emissions are field storage tanks, pneumatic devices (high bleed and low bleed), shallow water offshore oil platforms, and chemical injection pumps. These five sources together account for 98.5 percent of the non-combustion CO_2 emissions from this source category, while the remaining 1.5 percent of the

Table 3-38: CH_4 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Stage	1990	1995	2000	2005	2006	2007
Production Field Operations	**33.2**	**31.3**	**29.6**	**27.6**	**27.6**	**28.1**
Pneumatic Device Venting	10.3	9.7	9.0	8.3	8.3	8.4
Tank Venting	3.8	3.4	3.2	2.8	2.8	2.8
Combustion & Process Upsets	1.9	1.7	1.6	1.5	1.5	1.5
Misc. Venting & Fugitives	16.8	16.0	15.3	14.5	14.6	15.0
Wellhead Fugitives	0.5	0.5	0.5	0.4	0.4	0.4
Crude Oil Transportation	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Refining	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**
Total	**33.9**	**32.0**	**30.3**	**28.3**	**28.3**	**28.8**

Note: Totals may not sum due to independent rounding.

Table 3-39: CH_4 Emissions from Petroleum Systems (Gg)

Stage	1990	1995	2000	2005	2006	2007
Production Field Operations	**1,581**	**1,493**	**1,408**	**1,314**	**1,314**	**1,338**
Pneumatic Device Venting	489	463	428	397	396	398
Tank Venting	179	161	154	135	135	135
Combustion & Process Upsets	88	82	76	71	71	72
Misc. Venting & Fugitives	799	762	727	691	694	716
Wellhead Fugitives	26	25	22	19	17	18
Crude Oil Transportation	**7**	**6**	**5**	**5**	**5**	**5**
Refining	**25**	**25**	**28**	**28**	**28**	**27**
Total	**1,613**	**1,524**	**1,441**	**1,346**	**1,346**	**1,370**

Note: Totals may not sum due to independent rounding.

Table 3-40: CO_2 Emissions from Petroleum Systems (Tg CO_2 Eq.)

Stage	1990	1995	2000	2005	2006	2007
Production Field Operations	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Pneumatic Device Venting	+	+	+	+	+	+
Tank Venting	0.3	0.3	0.3	0.2	0.2	0.2
Misc. Venting & Fugitives	+	+	+	+	+	+
Wellhead Fugitives	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+ Less than 0.05 Tg CO_2 Eq.

Table 3-41: CO_2 Emissions from Petroleum Systems (Gg)

Stage	1990	1995	2000	2005	2006	2007
Production Field Operations	**376**	**341**	**325**	**287**	**288**	**287**
Pneumatic Device Venting	27	26	24	22	22	22
Tank Venting	328	296	283	248	249	247
Misc. Venting & Fugitives	18	18	17	16	16	16
Wellhead Fugitives	1	1	1	1	1	1
Total	**376**	**341**	**325**	**287**	**288**	**287**

Note: Totals may not sum due to independent rounding.

emissions is distributed among 24 additional activities within the three categories: vented, fugitive and process upsets.

Crude Oil Transportation. Crude oil transportation activities account for less than one half of one percent of total CH_4 emissions from the oil industry. Venting from tanks and marine vessel loading operations accounts for 62 percent of CH_4 emissions from crude oil transportation. Fugitive emissions, almost entirely from floating roof tanks, account for 19 percent. The remaining 19 percent is distributed among six additional sources within these two categories. Emissions from pump engine drivers and heaters were not estimated due to lack of data.

Crude Oil Refining. Crude oil refining processes and systems account for slightly less than two percent of total CH_4 emissions from the oil industry because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is an insignificant amount of CH_4 in all refined products. Within refineries, vented emissions account for about 87 percent of the emissions, while fugitive and combustion emissions account for approximately six and seven percent, respectively. Refinery system blowdowns for maintenance and the process of asphalt blowing—with air, to harden the asphalt—are the primary venting contributors. Most of the fugitive CH_4 emissions from refineries are from leaks in the fuel gas system. Refinery combustion emissions include small amounts of unburned CH_4 in process heater stack emissions and unburned CH_4 in engine exhausts and flares.

Methodology

The methodology for estimating CH_4 emissions from petroleum systems is a bottom-up approach, based on comprehensive studies of CH_4 emissions from U.S. petroleum systems (EPA 1996, EPA 1999). These studies combined emission estimates from 64 activities occurring in petroleum systems from the oil wellhead through crude oil refining, including 33 activities for crude oil production field operations, 11 for crude oil transportation activities, and 20 for refining operations. Annex 3.5 provides greater detail on the emission estimates for these 64 activities. The estimates of CH_4 emissions from petroleum systems do not include emissions downstream of oil refineries because these emissions are very small compared to CH_4 emissions upstream of oil refineries.

The methodology for estimating CH_4 emissions from the 64 oil industry activities employs emission factors initially developed by EPA (1999) and activity factors that are based on three EPA studies (1996, 1999 and 2005). Emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment item or per activity) by their corresponding activity factor (e.g., equipment count or frequency of activity). The report provides emission factors and activity factors for all activities except those related to offshore oil production and field storage tanks. For offshore oil production, two emission factors were calculated using data collected over a one-year period for all federal offshore platforms (EPA 2005, MMS 2004). One emission factor is for oil platforms in shallow water, and one emission factor is for oil platforms in deep water. Emission factors are held constant for the period 1990 through 2007. The number of platforms in shallow water and the number of platforms in deep water are used as activity factors and are taken from Minerals Management Service statistics (MMS 2008a-c). For oil storage tanks, the emissions factor was calculated from API TankCalc data as the total emissions per barrel of crude charge (EPA 1999).

The methodology for estimating CO_2 emissions from petroleum systems combines vented, fugitive and process upset emissions sources from 29 activities for crude oil production field operations. Emissions are estimated for each activity by multiplying emission factors by their corresponding activity factors. The emission factors for CO_2 are estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas. The only exceptions to this methodology are the emission factors for crude oil storage tanks, which are obtained from API TankCalc simulation runs.

Activity factors for the years 1990 through 2007 were collected from a wide variety of statistical resources. For some years, complete activity factor data were not available. In such cases, one of three approaches was employed. Where appropriate, the activity factor was calculated from related statistics using ratios developed for EPA (1996). For example, EPA (1996) found that the number of heater treaters (a source of CH_4 emissions) is related to both number of producing wells and annual production. To estimate the activity factor for heater treaters, reported statistics for wells and production were used, along with the ratios developed for EPA (1996). In other cases, the activity factor was held constant from 1990 through 2007 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable. The CH_4 and CO_2 sources in the production sector share common activity factors. See Annex 3.5 for additional detail.

Nearly all emission factors were taken from EPA (1995, 1996, 1999). The remaining emission factors were taken from EPA default values in (EPA 2005) and the consensus of industry peer review panels.

Among the more important references used to obtain activity factors are the Energy Information Administration annual and monthly reports (EIA 1990 through 2007, 1990 through 2008, 1995 through 2008a-b), *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, MMS reports (MMS 2001, 2008a-c), analysis of MMS data (EPA 2005, MMS 2004), the *Oil & Gas Journal* (OGJ 2008a,b), the Interstate Oil and Gas Compact Commission (IOGCC 2008), and the United States Army Corps of Engineers (1995–2008).

Uncertainty

This section describes the analysis conducted to quantify uncertainty associated with the estimates of emissions from petroleum systems. Performed using @RISK software and the IPCC-recommended Tier 2 methodology (Monte Carlo Simulation technique), the method employed 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.

The detailed, bottom-up inventory analysis used to evaluate U.S. petroleum systems reduces the uncertainty related to the CH_4 emission estimates in comparison to a top-down approach. However, some uncertainty still remains. Emission factors and activity factors are based on a combination of measurements, equipment design data, engineering calculations and studies, surveys of selected facilities and statistical reporting. Statistical uncertainties arise from natural variation in measurements, equipment types, operational variability and survey and statistical methodologies. Published activity factors are not available every year for all 64 activities analyzed for petroleum systems; therefore, some are estimated. Because of the dominance of the seven major sources, which account for 93.1 percent of the total methane emissions, the uncertainty surrounding these seven sources has been estimated most rigorously, and serves as the basis for determining the overall uncertainty of petroleum systems emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-42. Because the top emission sources have not changed from 2006, the relative uncertainty ranges computed for 2006 and published in the previous Inventory were taken as valid and applied to the 2007 inventory emission estimates. Petroleum systems CH_4 emissions in 2007 were estimated to be between 20.7 and 70.2 Tg CO_2 Eq., while CO_2 emissions were estimated to be

Table 3-42: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Petroleum Systems	CH_4	28.8	20.7	70.2	-28%	+144%
Petroleum Systems	CO_2	0.3	0.2	0.7	-28%	+144%

[a] Range of 2006 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.

Box 3-3: 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 CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the current Inventory, emissions from naturally-produced CO_2 are estimated based on the application.

In the current Inventory, the CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section. The naturally-occurring CO_2 used in EOR operations is assumed to be fully sequestered. Additionally, all anthropogenic CO_2 emitted from natural gas processing and ammonia plants is assumed to be emitted to the atmosphere, regardless of whether the CO_2 is captured or not. These emissions are currently included in the Natural Gas Systems and the Ammonia Production sections of the Inventory, respectively.

IPCC (2006) includes, for the first time, methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emissions estimates for geologic storage.

In October 2007, the U.S. EPA announced plans to develop regulations for geologic sequestration of CO_2 under the EPA Underground Injection Control Program. Given that the regulatory process is in its early phases, and site-specific emissions estimates are not yet available, emissions estimates from CO_2 capture, transport, injection and geologic storage are not yet included in national totals. Preliminary estimates indicate that the amount of CO_2 captured from industrial and natural sites, as well as fugitive emissions from pipelines is 40.0 Tg CO_2 (40,044 Gg CO_2) (see Table 3-43 and Table 3-44). Site-specific monitoring and reporting data for CO_2 injection sites (i.e., EOR operations) were not readily available; therefore, these estimates assume all CO_2 is emitted.

Table 3-43: Potential Emissions from CO_2 Capture and Transport (Tg CO_2 Eq.)

Stage	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**
Acid Gas Removal Plants	4.8	3.7	2.3	6.0	6.4	6.3
Naturally Occurring CO_2	20.8	22.5	23.2	28.3	30.2	33.1
Ammonia Production Plants	0.0	0.7	0.7	0.7	0.7	0.7
Pipelines Transporting CO_2	0.0	0.0	0.0	0.0	0.0	0.0
Total	**25.6**	**26.9**	**26.1**	**34.9**	**37.3**	**40.0**

Table 3-44: Potential Emissions from CO_2 Capture and Transport (Gg)

Stage	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**
Acid Gas Removal Plants	4,832	3,672	2,264	5,992	6,417	6,282
Naturally Occurring CO_2	20,811	22,547	23,208	8,267	30,224	33,086
Ammonia Production Plants	0	676	676	676	676	676
Pipelines Transporting CO_2	8	8	8	7	8	8
Total	**25,643**	**26,896**	**26,149**	**34,935**	**37,318**	**40,044**

between 0.2 and 0.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 28 percent below to 144 percent above the 2007 emission estimates of 28.8 and 0.3 Tg CO_2 Eq. for CH_4 and CO_2, respectively.

Recalculations Discussion

All revisions were due to updating previous years' data with revised data from existing data sources.

Planned Improvements

As noted above, nearly all emission factors used in the development of the petroleum systems estimates were taken from EPA (1995, 1996, 1999), with the remaining emission factors taken from EPA default values (EPA 2005) and a consensus of industry peer review panels. These emission factors will be reviewed as part of future inventory work. Results of this review and analysis will be incorporated into future Inventories, as appropriate.

3.7. Incineration of Waste (IPCC Source Category 1A5)

Incineration is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000b, Goldstein and Matdes 2001, Kaufman et al. 2004a, Simmons et al. 2006, ArSova et al. 2008). In the context of this section, waste includes all municipal solid waste (MSW) as well as tires. In the United States, almost all incineration of MSW occurs at waste-to-energy facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Energy chapter. Similarly, tires are combusted for energy recovery in industrial and utility boilers. Incineration of waste results in conversion of the organic inputs to CO_2. According to IPCC guidelines, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste incineration are calculated by estimating the quantity of waste combusted and the fraction of the waste that is C derived from fossil sources.

Most of the organic materials in 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—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, tires (which contain 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 (viz., most incineration occurs outside of MSW combustion facilities).

Approximately 32 million metric tons of waste was incinerated in the United States in 2007 (EPA 2008). Carbon dioxide emissions from incineration of waste rose 91 percent since 1990, to an estimated 20.8 Tg CO_2 Eq. (20,786 Gg) in 2007, as the volume of synthetic fibers and other fossil C-containing materials in waste increased (see Table 3-45 and Table 3-46). Waste incineration is also a source of N_2O emissions (De Soete 1993). Nitrous oxide emissions from the incineration of waste were estimated to be 0.4 Tg CO_2 Eq. (1 Gg N_2O) in 2007, and have not changed significantly since 1990.

Methodology

Emissions of CO_2 from the incineration of waste include CO_2 generated by the incineration of plastics, synthetic fibers, and synthetic rubber, as well as the incineration of synthetic rubber and carbon black in 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

Table 3-45: CO_2 and N_2O Emissions from the Incineration of Waste (Tg CO_2 Eq.)

Gas/Stage	1990	1995	2000	2005	2006	2007
CO_2	**10.9**	**15.7**	**17.5**	**19.5**	**19.8**	**20.8**
Plastics	8.0	10.3	11.8	12.8	12.9	13.6
Synthetic Rubber in Tires	0.2	0.8	0.9	1.2	1.2	1.2
Carbon Black in Tires	0.2	1.1	1.2	1.6	1.6	1.6
Synthetic Rubber in MSW	1.3	1.6	1.6	1.8	1.8	2.0
Synthetic Fibers	1.2	1.8	2.0	2.2	2.3	2.4
N_2O	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**11.4**	**16.2**	**17.9**	**19.9**	**20.2**	**21.2**

Table 3-46: CO_2 and N_2O Emissions from the Incineration of Waste (Gg)

Gas/Stage	1990	1995	2000	2005	2006	2007
CO_2	**10,950**	**15,712**	**17,485**	**19,532**	**19,824**	**20,786**
Plastics	7,976	10,347	11,766	12,782	12,920	13,622
Synthetic Rubber in Tires	191	841	893	1,207	1,207	1,207
Carbon Black in Tires	249	1,099	1,167	1,579	1,579	1,579
Synthetic Rubber in MSW	1,334	1,596	1,636	1,752	1,788	2,000
Synthetic Fibers	1,200	1,830	2,023	2,212	2,330	2,378
N_2O	**2**	**1**	**1**	**1**	**1**	**1**

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, as well as carbon black. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. Emissions of CO_2 were calculated based on the number of scrap tires used for fuel and the synthetic rubber and carbon black content of the tires.

More detail on the methodology for calculating emissions from each of these waste incineration sources is provided in Annex 3.6.

For each of the methods used to calculate CO_2 emissions from the incineration of waste, data on the quantity of product combusted and the C content of the product are needed. For plastics, synthetic rubber, and synthetic fibers, the amount of material in municipal solid wastes and its portion incinerated were taken from the *Characterization of Municipal Solid Waste in the United States* (EPA 2000b, 2002, 2003, 2005a, 2006b, 2007, 2008) and detailed unpublished backup data for some years not shown in the reports (Schneider 2007). For synthetic rubber and carbon black in scrap tires, information was obtained from *U.S. Scrap Tire Markets in the United States 2005 Edition* (RMA 2006) and *Scrap Tires, Facts and Figures* (STMC 2000 through 2003, 2006). For 2006 and 2007, synthetic rubber data is set equal to 2005 due to a lack of more recently available data.

Average C contents for the “Other” plastics category, synthetic rubber in municipal solid wastes, and synthetic fibers were calculated from 1998 production statistics, which divide their respective markets by chemical compound. Information about scrap tire composition was taken from the Scrap Tire Management Council’s Internet site (STMC 2006).

The assumption that 98 percent of organic C is oxidized (which applies to all waste incineration categories for CO_2 emissions) was reported in EPA’s life cycle analysis of greenhouse gas emissions and sinks from management of solid waste (EPA 2006a).

Incineration of waste also results in emissions of N_2O. These emissions were calculated as a function of the total estimated mass of waste incinerated and an emission factor.

Table 3-47: Municipal Solid Waste Generation (Metric Tons) and Percent Combusted

Year	Waste Generation	Incinerated (%)
1990	266,365,714	11.5
1995	296,390,405	10.0
2000	371,071,109	7.0
2001	353,086,962[a]	7.4[a]
2002	335,102,816	7.7
2003	343,482,645[b]	7.6[b]
2004	351,862,474	7.4
2005	363,274,720	7.2
2006	374,686,965	6.9
2007	374,686,965[c]	6.9[c]

[a] Interpolated between 2000 and 2002 values.
[b] Interpolated between 2002 and 2004 values.
[c] Assumed equal to 2006 value.
Source: ArSova et al. (2008).

The N_2O emission estimates are based on different data sources than the CO_2 emission estimates. As noted above, N_2O emissions are a function of total waste incinerated in each year; for 1990 through 2006, these data were derived from the information published in *BioCycle* (ArSova et al. 2008). Data on total waste incinerated was not available for 2007, so this value was assumed to equal the most recent value available (2006). Table 3-47 provides data on municipal solid waste generation and percentage combusted for the total waste stream. The emission factor of N_2O emissions per quantity of municipal solid waste combusted is an average of values from IPCC's *Good Practice Guidance* (2000).

Uncertainty

A Tier 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste. IPCC Tier 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. Uncertainty estimates and distributions for waste generation variables (i.e., plastics, synthetic rubber, and textiles generation) were obtained through a conversation with one of the authors of the *Municipal Solid Waste in the United States* reports. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the other variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW incineration rate; fraction oxidized; missing data on waste composition; average C content of waste components; assumptions on the synthetic/biogenic C ratio; and combustion conditions affecting N_2O emissions. The highest levels of uncertainty surround the variables that are based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-48. Waste incineration CO_2 emissions in 2007 were estimated to be between 15.2 and 25.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 27 percent below to 20 percent above the 2007 emission estimate of 20.8 Tg CO_2 Eq. Also at a 95 percent confidence level, Waste incineration N_2O emissions in 2007 were estimated to be between 0.1 and 1.2 Tg CO_2

Table 3-48: Tier 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	20.8	15.2	25.0	-27%	+20%
Incineration of Waste	N_2O	0.4	0.1	1.2	-71%	+191%

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

Eq. This indicates a range of 71 percent below to 191 percent above the 2007 emission estimate of 0.4 Tg CO_2 Eq.

QA/QC and Verification

A source-specific QA/QC 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 incineration of waste calculations.

Recalculations Discussion

This emissions source was previously known as Municipal Solid Waste Combustion.

Planned Improvements

Additional data sources for calculating an N_2O emission factor for U.S. incineration of waste may be investigated. In conjunction with its efforts to develop methods for reporting GHG emissions from various sources, the use of new techniques using radiochemistry methods to directly measure the fossil C content of flue gas from the incineration of waste may also be investigated.

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-CH_4 volatile organic compounds (NMVOCs) from energy-related activities from 1990 to 2007 are reported in Table 3-49.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends Web site. 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

Table 3-49: NO_x, CO, and NMVOC Emissions from Energy-Related Activities (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
NO_x	**20,829**	**20,429**	**18,338**	**15,033**	**14,129**	**13,687**
Mobile Combustion	10,920	10,622	10,310	8,757	8,271	7,831
Stationary Combustion	9,689	9,619	7,802	5,857	5,445	5,445
Oil and Gas Activities	139	100	111	321	316	314
Incineration of Waste	82	88	114	98	98	97
International Bunker Fuels[a]	*2,020*	*1,566*	*1,344*	*1,705*	*1,719*	*1,712*
CO	**125,640**	**104,402**	**89,714**	**69,060**	**64,876**	**61,231**
Mobile Combustion	119,360	97,630	83,559	62,519	58,322	54,678
Stationary Combustion	5,000	5,383	4,340	4,778	4,792	4,792
Incineration of Waste	978	1,073	1,670	1,439	1,438	1,438
Oil and Gas Activities	302	316	146	324	323	323
International Bunker Fuels[a]	*130*	*124*	*128*	*133*	*130*	*127*
NMVOCs	**12,620**	**10,538**	**8,952**	**8,530**	**8,198**	**7,903**
Mobile Combustion	10,932	8,745	7,229	6,292	5,954	5,672
Stationary Combustion	912	973	1,077	1,450	1,470	1,470
Oil and Gas Activities	554	582	388	545	535	526
Incineration of Waste	222	237	257	243	239	234
International Bunker Fuels[a]	*61*	*50*	*45*	*54*	*54*	*54*

[a] These values are presented for informational purposes only and are not included or are already accounted for in totals.

Note: Totals may not sum due to independent rounding.

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.

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

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.

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 currently 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.[39] These decisions are reflected in the *Revised 1996 IPCC Guidelines*, as well as the *2006 IPCC Guidelines*, 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/UNEP/OECD/IEA 1997).[40]

Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O. Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[41] 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.[42]

Emissions of CO_2 from aircraft are essentially a function of fuel use. Methane and N_2O emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Methane is the product of incomplete combustion and occurs mainly during the landing and take-off phases. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase. International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger-carrying, military (i.e., Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions,

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[39] 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).

[40] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[41] 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).

[42] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

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 2007 from the combustion of international bunker fuels from both aviation and marine activities were 109.9 Tg CO_2 Eq., or five percent below emissions in 1990 (see Table 3-50 and Table 3-51). Although emissions from international flights departing from the United States have increased (14 percent), emissions from international shipping voyages departing the United States have decreased by 18 percent since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 and N_2O were also emitted.

Methodology

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under CO_2 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 3.7 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 (2008) and USAF (1998), and heat content for jet fuel was taken from EIA (2008). A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.7 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Table 3-50: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (Tg CO_2 Eq.)

Gas/Mode	1990	1995	2000	2005	2006	2007
CO_2	**114.3**	**101.6**	**99.0**	**111.5**	**110.5**	**108.8**
Aviation	46.4	51.2	57.7	56.4	54.6	52.7
Marine	68.0	50.4	41.3	55.1	56.0	56.0
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	+	+	+	+	+	+
Marine	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**1.1**	**0.9**	**0.9**	**1.0**	**1.0**	**1.0**
Aviation	0.5	0.6	0.6	0.6	0.6	0.6
Marine	0.5	0.4	0.3	0.4	0.4	0.4
Total	**115.6**	**102.7**	**100.0**	**112.7**	**111.7**	**109.9**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-51: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (Gg)

Gas/Mode	1990	1995	2000	2005	2006	2007
CO_2	**114,330**	**101,620**	**98,966**	**111,487**	**110,520**	**108,756**
Aviation	46,378	51,196	57,694	56,424	54,564	52,740
Marine	67,952	50,425	41,272	55,063	55,956	56,016
CH_4	**8**	**6**	**6**	**7**	**7**	**7**
Aviation	2	2	2	2	2	2
Marine	7	5	4	5	5	5
N_2O	**3**	**3**	**3**	**3**	**3**	**3**
Aviation	2	2	2	2	2	2
Marine	2	1	1	1	1	1

Note: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). For aircraft emissions, the following values, in units of grams of pollutant per kilogram of fuel consumed (g/kg), were employed: 0.09 for CH_4 and 0.1 for N_2O For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.32 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on aircraft fuel consumption were derived from FAA's System for assessing Aviation Global Emissions (SAGE) Model (FAA 2006). International aviation bunker fuel consumption from 1990–2007 was calculated by assigning the difference between the sum of domestic activity data (in TBtu) from SAGE and the reported EIA transportation jet fuel consumption to the international bunker fuel category for jet fuel from EIA (2008). 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 by the Defense Energy Support Center, under DoD's Defense Logistics Agency (DESC 2008). 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 3-52. See Annex 3.7 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 1991 through 2008) for 1990 through 2001, and 2007, 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 DESC (2008). The total amount of fuel provided to naval vessels was reduced by 13 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 3-53.

Table 3-52: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	1995	2000	2005	2006	2007
U.S. and Foreign Carriers	4,932	5,462	6,158	6,022	5,823	5,629
U.S. Military	862	581	480	462	400	410
Total	**5,794**	**6,043**	**6,638**	**6,484**	**6,223**	**6,039**

Note: Totals may not sum due to independent rounding.

Table 3-53: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	1995	2000	2005	2006	2007
Residual Fuel Oil	4,781	3,495	2,967	3,881	4,004	4,059
Distillate Diesel Fuel & Other	617	573	290	444	446	358
U.S. Military Naval Fuels	522	334	329	471	414	444
Total	**5,920**	**4,402**	**3,586**	**4,796**	**4,864**	**4,861**

Note: Totals may not sum due to independent rounding.

Uncertainty

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.[43] 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, emission 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 estimates 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 CO_2 in the *Revised 1996 IPCC Guidelines* is to use data by specific aircraft type (IPCC/UNEP/OECD/IEA 1997). The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[44]

There is also concern as to the reliability of the existing DOC (1991 through 2008) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

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[43] See uncertainty discussions under CO_2 Emissions from Fossil Fuel Combustion.

[44] 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 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.

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 CO_2, CH_4, and N_2O 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.

Recalculations Discussion

Historical activity data for aviation was revised for both U.S. and foreign carriers. International jet fuel bunkers are now calculated in tandem with the domestic jet fuel estimates. EPA performs the analysis for domestic activity data (in TBtu), as described in the CO_2 from fossil fuel combustion section, and, using that calculated total for domestic in comparison with EIA's total consumption activity data, assigns the remainder to the jet fuel bunkers consumption. The previous method for international jet fuel bunkers were calculated based upon DOT (1991 through 2008) and BEA (1991 through 2005) data for the years 1990–1999 and 2006–2007 and estimated by FAA (2006) for 2000–2005. That data is still collected and used to quality assure the new method. The new method is understood to reduce the uncertainty of the domestic emissions calculation, as it relies on one dataset, rather than the multiple datasets that were used in the previous method for international jet fuel bunkers. Distillate and residual fuel oil consumption by cargo or passenger carrying marine vessels from 2003 through 2006 was revised using DHS (2008), and 2002 distillate and residual fuel oil consumption was interpolated to adjust inconsistencies in reported fuel consumption data. These historical data changes resulted in changes to the emission estimates for 1990 through 2006, which averaged to an annual increase in emissions from international bunker fuels of 6.6 Tg CO_2 Eq. (7.0 percent) in CO_2 emissions, an annual increase of less than 0.1 Tg CO_2 Eq. (14 percent) in CH_4 emissions, and an annual increase of 0.1 Tg CO_2 Eq. (12 percent) in N_2O emissions.

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 from corn and woody crops generates CO_2. However, in the long run the CO_2 emitted from biomass consumption does not increase atmospheric CO_2 concentrations, assuming that the biogenic C emitted is offset by the uptake of CO_2 that results from the growth of new biomass. As a result, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel-based emissions and are not included in the U.S. totals. Net C fluxes from changes in biogenic C reservoirs in wooded or crop lands are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

In 2007, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electricity generation sectors were approximately 209.8 Tg CO_2 Eq. (209,785 Gg) (see Table 3-54 and Table 3-55). As the largest consumer of woody biomass, the industrial sector was responsible for 65 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 23 percent of the total, while the commercial and electricity generation sectors accounted for the remainder.

Biomass-derived fuel consumption in the United States consisted primarily of ethanol use in the transportation sector. Ethanol is primarily produced from corn grown in the Midwest, and was used mostly in the Midwest and South. Pure ethanol can be combusted, or it can be mixed with gasoline as a supplement or octane-enhancing agent. The most common mixture is a 90 percent gasoline, 10 percent ethanol blend known as gasohol. Ethanol and ethanol blends are often used to fuel public transport vehicles such as buses, or centrally fueled fleet vehicles. These fuels burn cleaner than gasoline (i.e., lower in NO_x and hydrocarbon

Table 3-54: CO_2 Emissions from Wood Consumption by End-Use Sector (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2005	2006	2007
Industrial	135.3	155.1	153.6	136.3	142.2	136.7
Residential	59.8	53.6	43.3	46.4	42.3	47.4
Commercial	6.8	7.5	7.4	7.2	6.7	6.7
Electricity Generation	13.3	12.9	13.9	19.1	18.7	18.9
Total	**215.2**	**229.1**	**218.1**	**208.9**	**209.9**	**209.8**

Note: Totals may not sum due to independent rounding.

Table 3-55: CO_2 Emissions from Wood Consumption by End-Use Sector (Gg)

End-Use Sector	1990	1995	2000	2005	2006	2007
Industrial	135,348	155,075	153,559	136,269	142,226	136,729
Residential	59,808	53,621	43,309	46,402	42,278	47,434
Commercial	6,779	7,463	7,370	7,182	6,675	6,675
Electricity Generation	13,252	12,932	13,851	19,074	18,748	18,947
Total	**215,186**	**229,091**	**218,088**	**208,927**	**209,926**	**209,785**

Note: Totals may not sum due to independent rounding.

emissions), and have been employed in urban areas with poor air quality. However, because ethanol is a hydrocarbon fuel, its combustion emits CO_2.

In 2007, the United States consumed an estimated 577 trillion Btu of ethanol, and as a result, produced approximately 38.0 Tg CO_2 Eq. (38,044 Gg) (see Table 3-56 and Table 3-57) of CO_2 emissions. Ethanol production and consumption has grown steadily every year since 1990, with the exception of 1996 due to short corn supplies and high prices in that year.

Methodology

Woody biomass emissions were estimated by applying two EIA gross heat contents (Lindstrom 2006) to U.S. consumption data (EIA 2008) (see Table 3-58), provided in energy units for the industrial, residential, commercial, and electric generation sectors. One heat content (16.953114 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.432359 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA

Table 3-56: CO_2 Emissions from Ethanol Consumption (Tg CO_2 Eq.)

End-Use Sector	1990	1995	2000	2005	2006	2007
Transportation	4.1	7.6	9.1	22.0	29.8	37.2
Industrial	0.1	0.1	0.1	0.5	0.6	0.8
Commercial	+	+	+	0.1	0.1	0.1
Total	**4.2**	**7.7**	**9.2**	**22.6**	**30.5**	**38.0**

+ Less than 0.05 Tg CO_2 Eq.

Table 3-57: CO_2 Emissions from Ethanol Consumption (Gg)

End-Use Sector	1990	1995	2000	2005	2006	2007
Transportation	4,066	7,570	9,077	22,034	29,758	37,168
Industrial	55	104	85	460	622	777
Commercial	33	9	25	59	80	100
Total	**4,155**	**7,683**	**9,188**	**22,554**	**30,459**	**38,044**

Table 3-58: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	1995	2000	2005	2006	2007
Industrial	1,442	1,652	1,636	1,452	1,515	1,457
Residential	580	520	420	450	410	460
Commercial	66	72	71	70	65	65
Electricity Generation	129	125	134	185	182	184
Total	**2,216**	**2,370**	**2,262**	**2,156**	**2,172**	**2,165**

Table 3-59: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	1995	2000	2005	2006	2007
Transportation	61.7	114.8	137.6	334.1	451.2	563.6
Industrial	0.8	1.6	1.3	7.0	9.4	11.8
Commercial	0.5	0.1	0.4	0.9	1.2	1.5
Total	**63.0**	**116.5**	**139.3**	**342.0**	**461.9**	**576.9**

emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 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 CO_2 with 100 percent efficiency. The emissions from ethanol consumption were calculated by applying an EIA emission factor of 17.99 Tg C/QBtu (Lindstrom 2006) to U.S. ethanol consumption estimates that were provided in energy units (EIA 2008) (see Table 3-59).

Uncertainty

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.

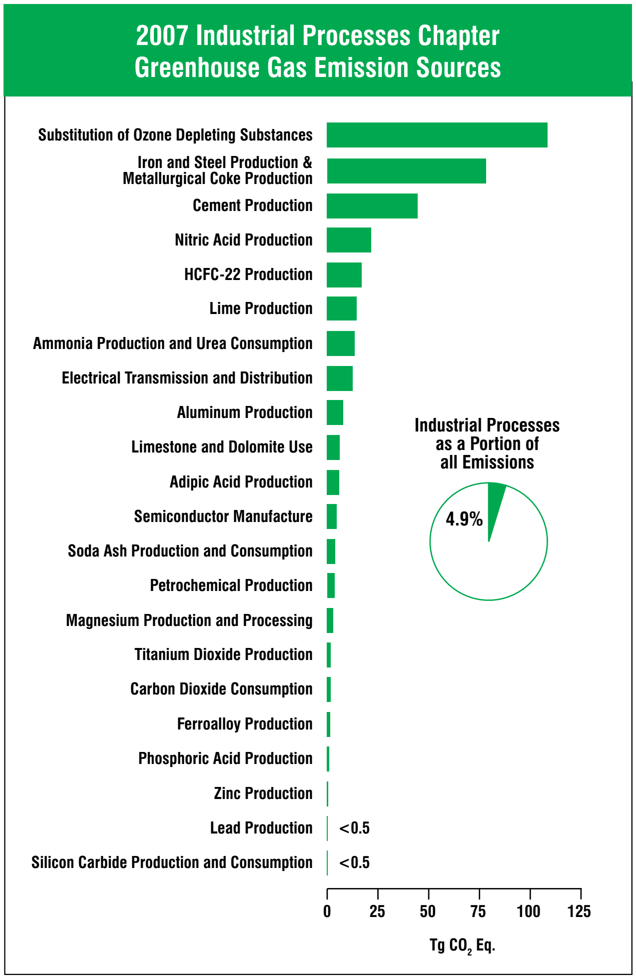
Recalculations Discussion

Wood consumption values were revised in 2001 through 2003, and 2005 through 2006 based on updated information from EIA's Annual Energy Review (EIA 2008). EIA (2008) also reported minor changes in wood consumption for all sectors in 2006. This adjustment of historical data for wood biomass consumption resulted in an average annual increase in emissions from wood biomass consumption of 0.6 Tg CO_2 Eq. (0.3 percent) from 1990 through 2006. Slight adjustments were made to ethanol consumption based on updated information from EIA (2008), which slightly decreased estimates for ethanol consumed. As a result of these adjustments, average annual emissions from ethanol consumption decreased by less than 0.1 Tg CO_2 Eq. (less than 0.1 percent).

4. Industrial Processes

Greenhouse gas emissions are produced as the byproducts of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically 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), or nitrous oxide (N_2O). The processes addressed in this chapter include iron and steel production, cement production, lime production, ammonia production and urea consumption, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and use, aluminum production, titanium dioxide production, CO_2 consumption, ferroalloy production, phosphoric acid production, zinc production, lead production, petrochemical production, silicon carbide production and consumption, nitric acid production, and adipic acid production (see Figure 4-1).

Figure 4-1



2007 Industrial Processes Chapter Greenhouse Gas Emission Sources

In addition to the three greenhouse gases listed above, there are also industrial sources of man-made fluorinated compounds called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The present contribution of these 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. Usage of HFCs for the substitution of ozone depleting substances is growing rapidly, as 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*. In addition to their use as ODS substitutes, HFCs, PFCs, SF_6, 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.

In 2007, industrial processes generated emissions of 353.8 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 5 percent of total U.S. greenhouse gas emissions. Carbon dioxide emissions from all industrial processes were 174.9 Tg CO_2 Eq. (174,939 Gg) in 2007, or 3 percent of total U.S. CO_2 emissions. CH_4 emissions from industrial processes resulted in emissions of approximately 1.7 Tg CO_2 Eq. (82 Gg) in 2007, which was less than 1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from adipic acid and nitric acid production were 27.6 Tg CO_2 Eq. (89 Gg) in 2007, or 9 percent of total U.S. N_2O emissions. In 2007, combined emissions of HFCs, PFCs and SF_6 totaled 149.5 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 9 percent from 1990 to 2007 despite decreases in emissions from several industrial processes, such as cement production, lime production, limestone and dolomite use, soda ash production and consumption, and electrical transmission and distribution. The increase in overall emissions was driven by a rise in the emissions originating from HCFC-22 production and, primarily, the emissions from the use of substitutes for ozone depleting substances.

Table 4-1 summarizes emissions for the Industrial Processes chapter in units of Tg CO_2 Eq., while unweighted native gas emissions in Gg are provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the common reporting format tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, and SF_6.

QA/QC and Verification Procedures

Tier 1 quality assurance and quality control procedures have been performed for all industrial process sources. For industrial process sources of CO_2 and CH_4 emissions, a detailed plan was developed and implemented. This plan was based on U.S. strategy, 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 procedures and checks of the emission factors, activity data, and methodologies used for estimating emissions from the relevant Industrial Processes sources. Examples of these procedures include, among others, 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.

The general method employed to estimate emissions for industrial processes, as recommended by the IPCC, involves multiplying production data (or activity data) for each process by an emission factor per unit of production. The uncertainty in the emission estimates is therefore generally a function of a combination of the uncertainties surrounding the production and emission factor variables. Uncertainty of activity data and the associated probability density functions for industrial processes CO_2 sources were estimated based on expert assessment of available qualitative and quantitative information. Uncertainty estimates and probability density functions for the emission factors used to calculate emissions from this source were devised based on IPCC recommendations.

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 plant-level production data and is influenced by the completeness of the survey response. The emission factors used were either 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 2007 inventory estimates from industrial processes 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

Table 4-1: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**197.6**	**198.6**	**193.2**	**171.1**	**175.9**	**174.9**
Iron and Steel Production and Metallurgical Coke Production	109.8	103.1	95.1	73.2	76.1	77.4
Iron and Steel Production	*104.3*	*98.1*	*90.7*	*69.3*	*72.4*	*73.6*
Metallurgical Coke Production	*5.5*	*5.0*	*4.4*	*3.8*	*3.7*	*3.8*
Cement Production	33.3	36.8	41.2	45.9	46.6	44.5
Ammonia Production & Urea Consumption	16.8	17.8	16.4	12.8	12.3	13.8
Lime Production	11.5	13.3	14.1	14.4	15.1	14.6
Limestone and Dolomite Use	5.1	6.7	5.1	6.8	8.0	6.2
Aluminum Production	6.8	5.7	6.1	4.1	3.8	4.3
Soda Ash Production and Consumption	4.1	4.3	4.2	4.2	4.2	4.1
Petrochemical Production	2.2	2.8	3.0	2.8	2.6	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.8	1.9	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	1.3	1.7	1.9
Ferroalloy Production	2.2	2.0	1.9	1.4	1.5	1.6
Phosphoric Acid Production	1.5	1.5	1.4	1.4	1.2	1.2
Zinc Production	0.9	1.0	1.1	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2
CH_4	**1.9**	**2.1**	**2.2**	**1.8**	**1.7**	**1.7**
Petrochemical Production	0.9	1.1	1.2	1.1	1.0	1.0
Iron and Steel Production and Metallurgical Coke Production	1.0	1.0	0.9	0.7	0.7	0.7
Iron and Steel Production	*1.0*	*1.0*	*0.9*	*0.7*	*0.7*	*0.7*
Metallurgical Coke Production	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+
N_2O	**35.3**	**39.6**	**28.1**	**24.6**	**24.2**	**27.6**
Nitric Acid Production	20.0	22.3	21.9	18.6	18.2	21.7
Adipic Acid Production	15.3	17.3	6.2	5.9	5.9	5.9
HFCs	**36.9**	**61.8**	**100.1**	**116.1**	**119.1**	**125.5**
Substitution of Ozone Depleting Substances[a]	0.3	28.5	71.2	100.0	105.0	108.3
HCFC-22 Manufacture	36.4	33.0	28.6	15.8	13.8	17.0
Semiconductor Manufacturing HFCs	0.2	0.3	0.3	0.2	0.3	0.3
PFCs	**20.8**	**15.6**	**13.5**	**6.2**	**6.0**	**7.5**
Aluminum Production	18.5	11.8	8.6	3.0	2.5	3.8
Semiconductor Manufacturing PFCs	2.2	3.8	4.9	3.2	3.5	3.7
SF_6	**32.8**	**28.1**	**19.2**	**17.9**	**17.1**	**16.5**
Electrical Transmission and Distribution	26.8	21.6	15.1	14.0	13.2	12.7
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.0
Semiconductor Manufacturing SF_6	0.5	0.9	1.1	1.0	1.0	0.8
Total	**325.2**	**345.8**	**356.3**	**337.6**	**343.9**	**353.8**

+ Does not exceed 0.05 Tg CO_2 Eq.

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

Note: Totals may not sum due to independent rounding.

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.

Table 4-2: Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
CO_2	**197,623**	**198,584**	**193,217**	**171,075**	**175,897**	**174,939**
Iron and Steel Production and Metallurgical Coke Production	109,760	103,116	95,062	73,190	76,100	77,370
Iron and Steel Production	*104,262*	*98,078*	*90,680*	*69,341*	*72,418*	*73,564*
Metallurgical Coke Production	*5,498*	*5,037*	*4,381*	*3,849*	*3,682*	*3,806*
Cement Production	33,278	36,847	41,190	45,910	46,562	44,525
Ammonia Production & Urea Consumption	16,831	17,796	16,402	12,849	12,300	13,786
Lime Production	11,533	13,325	14,088	14,379	15,100	14,595
Limestone and Dolomite Use	5,127	6,651	5,056	6,768	8,035	6,182
Aluminum Production	6,831	5,659	6,086	4,142	3,801	4,251
Soda Ash Production and Consumption	4,141	4,304	4,181	4,228	4,162	4,140
Petrochemical Production	2,221	2,750	3,004	2,804	2,573	2,636
Titanium Dioxide Production	1,195	1,526	1,752	1,755	1,876	1,876
Carbon Dioxide Consumption	1,416	1,422	1,421	1,321	1,709	1,867
Ferroalloy Production	2,152	2,036	1,893	1,392	1,505	1,552
Phosphoric Acid Production	1,529	1,513	1,382	1,386	1,167	1,166
Zinc Production	949	1,013	1,140	465	529	530
Lead Production	285	298	311	266	270	267
Silicon Carbide Production and Consumption	375	329	248	219	207	196
CH_4	**88**	**100**	**104**	**86**	**83**	**82**
Petrochemical Production	41	52	59	51	48	48
Iron and Steel Production and Metallurgical Coke Production	46	47	44	34	35	33
Iron and Steel Production	*46*	*47*	*44*	*34*	*35*	*33*
Metallurgical Coke Production	+	+	+	+	+	+
Ferroalloy Production	1	1	1	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+
N_2O	**114**	**128**	**91**	**79**	**78**	**89**
Nitric Acid Production	64	72	71	60	59	70
Adipic Acid Production	49	56	20	19	19	19
HFCs	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M
HCFC-22 Manufacture	+	3	3	1	1	1
Semiconductor Manufacturing HFCs	+	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**
Aluminum Production	M	M	M	M	M	M
Semiconductor Manufacturing PFCs	M	M	M	M	M	M
SF_6	**1**	**1**	**1**	**1**	**1**	**1**
Electrical Transmission and Distribution	+	1	1	1	1	1
Magnesium Production and Processing	+	+	+	+	+	+
Semiconductor Manufacturing SF_6	+	+	+	+	+	+

\+ Does not exceed 0.5 Gg.

M (Mixture of gases).

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

Note: Totals may not sum due to independent rounding.

4.1. Cement Production (IPCC Source Category 2A1)

Cement production is an energy- and raw-material-intensive process that results in the generation of CO_2 from both the energy consumed in making the cement and the chemical process itself.[1] Cement is produced in 37 states and Puerto Rico. Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,450°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. A very small amount of carbonates other than $CaCO_3$ and non-carbonates are also present in the raw material; however, for calculation purposes all of the raw material is assumed to be $CaCO_3$. 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) and used to make portland cement.[2]

In 2007, U.S. clinker production—including Puerto Rico—totaled 86,106 thousand metric tons (van Oss 2008b). The resulting emissions of CO_2 from 2007 cement production were estimated to be 44.5 Tg CO_2 Eq. (44,525 Gg) (see Table 4-3).

Table 4-3: CO_2 Emissions from Cement Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	33.3	33,278
1995	36.8	36,847
2000	41.2	41,190
2005	45.9	45,910
2006	46.6	46,562
2007	44.5	44,525

After falling in 1991 by 2 percent from 1990 levels, cement production emissions grew every year through 2006, and then decreased slightly from 2006 to 2007. Overall, from 1990 to 2007, emissions increased by 34 percent. Cement continues to be a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, have had considerable influence on cement production.

Methodology

Carbon dioxide emissions from cement production are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone) in the cement kiln. While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Carbon dioxide emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 65 percent (van Oss 2008c) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.51 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{\text{Clinker}} = 0.65\ \text{CaO} \times \left[\frac{44.01\ \text{g/mole}\ CO_2}{56.08\ \text{g/mole CaO}}\right]$$

$$= 0.51\ \text{tons}\ CO_2/\text{ton clinker}$$

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

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[1] The CO_2 emissions related to the consumption of energy for cement manufacture are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

[2] Approximately six percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime) and portland cement. Carbon dioxide emissions that result from the production of lime used to create masonry cement are included in the Lime Manufacture source category (van Oss 2008c).

Table 4-4: Clinker Production (Gg)

Year	Clinker
1990	64,355
1995	71,257
2000	79,656
2005	88,783
2006	90,045
2007	86,106

are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as 2 percent of the CO_2 emissions calculated from clinker production.[3] Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2006).[4]

The 1990 through 2007 activity data for clinker production (see Table 4-4) were obtained through a personal communication with Hendrik van Oss (van Oss 2008b) of the USGS and through the USGS *Minerals Yearbook: Cement Annual Report* (US Bureau of Mines 1990 through 1993, USGS 1995 through 2006). The data were compiled by USGS through questionnaires sent to domestic clinker and cement manufacturing plants.

Uncertainty

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 material is $CaCO_3$ when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent (van Oss 2008b). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create $CaCO_3$. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-5. Cement Production CO_2 emissions were estimated to be between 38.8 and 50.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 44.5 Tg CO_2 Eq.

Table 4-5: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	44.5	38.8	50.5	-13%	+13%

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

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[3] Default IPCC clinker and CKD emission factors were verified through expert consultation with the Portland Cement Association (PCA 2008) and van Oss (2008a).

[4] The 2 percent CO_2 addition associated with CKD is included in the emission estimate for completeness. The cement emission estimate also includes an assumption that all raw material is limestone ($CaCO_3$) when in fact a small percentage is likely composed of non-carbonate materials. Together these assumptions may result in a small emission overestimate (van Oss 2008c).

Recalculations

Estimates of CO_2 emissions from cement production were revised for 2006 to reflect updates to the clinker production data for that year.

Planned Improvements

Future improvements to the cement source category involve continued research into emission factors for clinker production and CKD. Research has been conducted into the accuracy and appropriateness of default emission factors and reporting methodology used by other organizations. As these methodologies continue to develop, the cement source category will be updated with any improvements to IPCC assumptions for clinker and CKD emissions.

4.2. Lime Production (IPCC Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water purification. For U.S. operations, the term “lime” actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce 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] In certain additional applications, lime reabsorbs CO_2 during use.

Lime production in the United States—including Puerto Rico—was reported to be 20,192 thousand metric tons in 2007 (USGS 2008). This resulted in estimated CO_2 emissions of 14.6 Tg CO_2 Eq. (or 14,595 Gg) (see Table 4-6 and Table 4-7).

Table 4-6: CO_2 Emissions from Lime Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	11.5	11,533
1995	13.3	13,325
2000	14.1	14,088
2005	14.4	14,379
2006	15.1	15,100
2007	14.6	14,595

Table 4-7: Potential, Recovered, and Net CO_2 Emissions from Lime Production (Gg)

Year	Potential	Recovered[a]	Net Emissions
1990	12,004	471	11,533
1995	14,019	694	13,325
2000	14,872	784	14,088
2005	15,131	752	14,379
2006	15,825	725	15,100
2007	15,264	669	14,595

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

The contemporary lime market is distributed across five end-use categories as follows: metallurgical uses, 36 percent; environmental uses, 29 percent; chemical and industrial uses, 22 percent; construction uses, 12 percent; and refractory dolomite, 1 percent. In the construction sector, lime is used to improve durability in plaster, stucco, and mortars, as well as to stabilize soils. In 2007, the amount of lime used for construction decreased by 8 percent from 2006 levels. This is most likely a result of increased prices for lime and the downturn in new home construction; total construction spending decreased by 3 percent and residential construction spending decreased by nearly 18 percent compared with 2006 (USGS 2008).

Lime production in 2007 decreased by 4 percent compared to 2006, owing to a downturn in major markets including construction, mining, and steel (USGS 2008). Overall, from 1990 to 2007, lime production has increased by 28 percent. Annual consumption for industrial/chemical

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[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.

and environmental lime consumption decreased by 1 percent and 4 percent, respectively (USGS 2008). The decrease in environmental production for environmental uses is attributed to a decrease in lime consumption for drinking water treatment, sludge treatment, and the utility power-plant market for flue gas desulfurization (USGS 2008). Lime production also decreased for metallurgical consumption, owing to a shift in steel production from basic oxygen furnaces (BOF) to electric arc furnaces (EAF). EAFs use iron and steel scrap as their primary iron source which contains fewer impurities and requires less than one-half of the lime per ton of steel produced than pig iron used by BOFs (USGS 2008).

Methodology

During the calcination stage of lime production, CO_2 is given off as a gas and normally exits the system with the stack gas. To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors. The emission factor is the product of a constant reflecting the mass of CO_2 released per unit of lime and the average calcium plus magnesium oxide (CaO + MgO) content for lime (95 percent for both types of lime) (IPCC 2006). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g } CO_2\text{/g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.87 \text{ g } CO_2\text{/g lime}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to $Ca(OH)_2$ and $[Ca(OH)_2 \bullet Mg(OH)_2]$ (IPCC 2000). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.3 percent for dolomitic hydrated lime.

Lime emission estimates were multiplied by a factor of 1.02 to account for lime kiln dust (LKD), which is produced as a byproduct during the production of lime (IPCC 2006).

Lime emission estimates were further adjusted to account for PCC producers and sugar refineries that recover CO_2 emitted by lime production facilities and use the captured CO_2 as an input into production or refining processes. For CO_2 recovery by sugar refineries, lime consumption estimates from USGS were multiplied by a CO_2 recovery factor to determine the total amount of CO_2 recovered from lime production facilities. According to industry surveys, sugar refineries use captured CO_2 for 100 percent of their CO_2 input (Lutter 2008). Carbon dioxide recovery by PCC producers was determined by multiplying estimates for the percentage CO_2 of production weight for PCC production at lime plants, by a CO_2 recovery factor of 93 percent for 2007 (Prillaman 2008). As data were only available for 2007, CO_2 recovery for the period 1990 through 2006 were extrapolated by determining a ratio of PCC production at lime facilities to lime consumption for PCC (USGS 2002 through 2007, 2008).

Lime production data (high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2007 (see Table 4-8) were obtained from USGS (1992 through 2007). Natural hydraulic

Table 4-8: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (Gg)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
1995	13,165	2,635	2,027	363	308
2000	14,300	3,000	1,550	421	200
2005	14,100	2,990	2,220	474	200
2006	15,000	2,950	2,370	409	200
2007	14,700	2,700	2,240	352	200

Table 4-9: Adjusted Lime Production[a] (Gg)

Year	High-Calcium	Dolomitic
1990	12,514	2,809
1995	14,700	3,207
2000	15,473	3,506
2005	15,781	3,535
2006	16,794	3,448
2007	16,396	3,156

[a] Minus water content of hydrated lime.

lime, which is produced from CaO and hydraulic calcium silicates, is not produced in the United States (USGS 2008). 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 *Good Practice Guidance* and is presented in Table 4-9 (USGS 1992 through 2007, IPCC 2000). The CaO and CaO•MgO contents of lime were obtained from IPCC (2006). Since data for the individual lime types (high calcium and dolomitic) was not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three year distribution from 1997 to 1999. Lime consumed by PCC producers and sugar refineries was obtained from USGS (1992 through 2007).

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of these products and recovery rates for sugar refineries and PCC manufacturers located at lime plants. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce PCC reacts with CO_2, whereas most of the lime used in steel-making reacts with impurities such as silica, sulfur, and aluminum compounds. A detailed accounting of lime use in the United States and further research into the associated processes are required to quantify the amount of CO_2 that is reabsorbed.[6]

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 not 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 C is present from the wood. Kraft mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin, and therefore is not included in inventory totals (Miner and Upton 2002).

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.

Uncertainties also remain surrounding recovery rates used for sugar refining and PCC production. The recovery rate for sugar refineries is based on two sugar beet processing and refining facilities located in California that use 100 percent recovered CO_2 from lime plants (Lutter 2008). This analysis assumes that all sugar refineries located on-site at lime plants

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[6] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[7] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$] and no CO_2 is released.

Table 4-10: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	14.6	13.5	15.9	-8%	+9%

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

also use 100 percent recovered CO_2. The recovery rate for PCC producers located on-site at lime plants is based on the 2007 value for PCC manufactured at commercial lime plants, given by the National Lime Association (Prillaman 2008).

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions were estimated to be between 13.5 and 15.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 9 percent above the emission estimate of 14.6 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from lime production were revised for years 1990 through 2006 to include estimates of CO_2 recovery from PCC production and sugar refining. On average, these revisions resulted in an annual decrease in emissions of approximately 13 percent.

Planned Improvements

Future improvements to the lime source category involve continued research into CO_2 recovery associated with lime use during sugar refining and PCC production. Two sugar refining facilities in California have been identified that capture CO_2 produced in lime kilns located on the same site as the sugar refinery (Lutter, 2008). Currently, data on CO_2 production by these lime facilities is unavailable. Future work will include research to determine the number of sugar refineries that employ the carbonation technique, the percentage of these that use captured CO_2 from lime production facilities, and the amount of CO_2 recovered per unit of lime production. Future research will also aim to improve estimates of CO_2 recovered as part of the PCC production process using estimates of PCC production and CO_2 inputs rather than lime consumption by PCC facilities.

4.3. Limestone and Dolomite Use (IPCC Source Category 2A3)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[8] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control. 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. For some of these applications, limestone is sufficiently heated during the process and generates CO_2 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 systems for utility and industrial plants, or as a raw material in glass manufacturing and magnesium production.

In 2007, approximately 13,075 thousand metric tons of limestone and 1,827 thousand metric tons of dolomite were consumed during production for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 6.2 Tg CO_2 Eq. (6,182 Gg) (see Table 4-11 and Table 4-12). Emissions in 2007 decreased 23 percent from the previous year and have increased 21 percent overall from 1990 through 2007.

Methodology

Carbon dioxide emissions were calculated by multiplying the quantity of limestone or dolomite consumed by the average C content, approximately 12.0 percent for limestone

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[8] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Table 4-11: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Flux Stone	2.6	3.2	2.1	2.7	4.5	2.0
Glass Making	0.2	0.5	0.4	0.4	0.7	0.3
Flue Gas Desulfurization	1.4	1.7	1.8	3.0	2.1	3.2
Magnesium Production	0.1	0.0	0.1	0.0	0.0	0.0
Other Miscellaneous Uses	0.8	1.2	0.7	0.7	0.7	0.7
Total	**5.1**	**6.7**	**5.1**	**6.8**	**8.0**	**6.2**

Notes: Totals may not sum due to independent rounding. "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Table 4-12: CO_2 Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1995	2000	2005	2006	2007
Flux Stone	2,593	3,198	2,104	2,650	4,492	1,959
Limestone	2,304	2,027	1,374	1,096	1,917	1,270
Dolomite	289	1,171	730	1,554	2,575	689
Glass Making	217	525	371	425	747	333
Limestone	189	421	371	405	717	333
Dolomite	28	103	0	20	31	0
Flue Gas Desulfurization	1,433	1,719	1,787	2,975	2,061	3,179
Magnesium Production	64	41	73	0	0	0
Other Miscellaneous Uses	819	1,168	722	718	735	711
Total	**5,127**	**6,651**	**5,056**	**6,768**	**8,035**	**6,182**

Notes: Totals may not sum due to independent rounding. "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

and 13.2 percent for dolomite (based on stoichiometry), and converting this value to CO_2. This methodology was used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining and then converting to CO_2 using a molecular weight ratio. Flux stone used during the production of iron and steel was deducted from the Limestone and Dolomite Use estimate and attributed to the Iron and Steel Production estimate.

Traditionally, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO_2 emissions. At the start of 2001, there were two magnesium production plants operating in the United States and they used different production methods. One plant produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions, while the other plant produced magnesium from magnesium chloride using a CO_2-emissions-free process called electrolytic reduction. However, the plant utilizing the dolomitic process ceased its operations prior to the end of 2001, so beginning in 2002 there were no emissions from this particular sub-use.

Consumption data for 1990 through 2007 of limestone and dolomite used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-13) were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (USGS 1993, 1995a through 2007a, 2008a). The production capacity data for 1990 through 2007 of dolomitic magnesium metal (see Table 4-14) also came from the USGS (1995b through 2007b, 2008b). The last plant in the United States that used the dolomitic production process for magnesium metal closed in 2001. The USGS does not mention this process in the 2007 *Minerals Yearbook: Magnesium*; therefore, it is assumed that this process continues to be non-existent in the United States (USGS 2008b). During 1990 and 1992, the

Table 4-13: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2005	2006	2007
Flux Stone	6,737	8,586	6,283	7,022	11,030	5,305
Limestone	5,804	5,734	4,151	3,165	5,208	3,477
Dolomite	933	2,852	2,132	3,857	5,822	1,827
Glass Making	489	1,174	843	962	1,693	757
Limestone	430	958	843	920	1,629	757
Dolomite	59	216	0	43	64	0
Flue Gas Desulfurization	3,258	3,908	4,061	6,761	4,683	7,225
Other Miscellaneous Uses	1,835	2,654	1,640	1,632	1,671	1,616
Total	**12,319**	**16,321**	**12,826**	**16,377**	**19,078**	**14,903**

Notes: "Other miscellaneous uses" includes chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Zero values for limestone and dolomite consumption for glass making result during years when the USGS reports that no limestone or dolomite are consumed for this use.

Table 4-14: Dolomitic Magnesium Metal Production Capacity (Metric Tons)

Year	Production Capacity
1990	35,000
1995	22,222
2000	40,000
2005	0
2006	0
2007	0

Note: Production capacity for 2002, 2003, 2004, 2005, 2006, and 2007 amounts to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002b through 2008b).

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.[9]

Uncertainty

The uncertainty levels presented in this section arise 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. Similarly, the quality of the limestone 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 and not the end user. Additionally, there is

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[9] This approach was recommended by USGS.

Table 4-15: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Limestone and Dolomite Use (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Limestone and Dolomite Use	CO_2	6.2	5.4	7.2	-12%	+16%

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

significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone used in glass making is especially high; however, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low. 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.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-15. Limestone and Dolomite Use CO_2 emissions were estimated to be between 5.4 and 7.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 16 percent above the emission estimate of 6.2 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from Limestone and Dolomite Use have been revised for the entire time series to accommodate minor revisions to the "unspecified uses" of limestone and dolomite identified by the USGS. On average, these revisions resulted in an annual decrease in emissions of 0.1 percent. Additionally, limestone and dolomite consumption data were updated to attribute emissions from limestone and dolomite used for iron and steel production to the Iron and Steel Production estimate. On average, this resulted in an additional decrease in emissions of 10 percent.

Planned Improvements

Future improvements to the limestone and dolomite source category involve research into the availability of limestone and dolomite end-use data. If sufficient data are available, limestone and dolomite used as process materials in source categories included in future Inventories (e.g., glass production, other process use of carbonates) may be removed from this section and will be reported under the appropriate source categories.

4.4. Soda Ash Production and Consumption (IPCC Source Category 2A4)

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. 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.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO_2 from Wyoming were calculated due to specifics regarding the production processes employed in the state.[10]

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[10] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona in the state. For a brief time, $NaHCO_3$ was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Because the trona is 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 4-16: CO_2 Emissions from Soda Ash Production and Consumption (Tg CO_2 Eq.)

Year	Production	Consumption	Total
1990	1.4	2.7	4.1
1995	1.6	2.7	4.3
2000	1.5	2.7	4.2
2005	1.7	2.6	4.2
2006	1.6	2.5	4.2
2007	1.7	2.5	4.1

Note: Totals may not sum due to independent rounding.

Table 4-17: CO_2 Emissions from Soda Ash Production and Consumption (Gg)

Year	Production	Consumption	Total
1990	1,431	2,710	4,141
1995	1,607	2,698	4,304
2000	1,529	2,652	4,181
2005	1,655	2,573	4,228
2006	1,626	2,536	4,162
2007	1,675	2,465	4,140

Note: Totals may not sum due to independent rounding.

During the production process used in Wyoming, trona ore is treated to produce soda ash. Carbon dioxide is generated as a byproduct of this reaction, and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed.

In 2007, CO_2 emissions from the production of soda ash from trona were approximately 1.7 Tg CO_2 Eq. (1,675 Gg). Soda ash consumption in the United States generated 2.5 Tg CO_2 Eq. (2,465 Gg) in 2007. Total emissions from soda ash production and consumption in 2007 were 4.1 Tg CO_2 Eq. (4,140 Gg) (see Table 4-16 and Table 4-17). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2007 decreased by approximately 0.5 percent from the previous year, and have decreased overall by less than 0.5 percent since 1990.

The United States represents about one-fourth of total world soda ash output. The approximate distribution of soda ash by end-use in 2007 was glass making, 49 percent; chemical production, 30 percent; soap and detergent manufacturing, 8 percent; distributors, 5 percent; flue gas desulfurization, 2 percent; water treatment, 2 percent; pulp and paper production, 2 percent; and miscellaneous, 3 percent (USGS 2008).

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. While Chinese soda ash production appears to be stabilizing, U.S. competition in Asian markets is expected to continue. Despite this competition, U.S. soda ash production is expected to increase by about 0.5 percent annually over the next five years (USGS 2006).

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 following chemical reaction:

$$\underset{\text{[trona]}}{2(Na_3(CO_3)(HCO_3)\bullet 2H_2O)} \rightarrow \underset{\text{[soda ash]}}{3Na_2CO_3} + 5H_2O + CO_2$$

Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO_2, or an emission factor of 0.097 metric tons CO_2 per metric ton trona (IPCC 2006). Thus, the 17.2 million metric tons of trona mined in 2007 for soda ash production (USGS 2008) resulted in CO_2 emissions of approximately 1.7 Tg CO_2 Eq. (1,675 Gg).

Once produced, most soda ash is consumed in glass and chemical production, with minor amounts in soap and detergents, pulp and paper, flue gas desulfurization and water treatment. As soda ash is consumed for these purposes, additional CO_2 is usually emitted. In these applications, it is assumed that one mole of C is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of C (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed.

The activity data for trona production and soda ash consumption (see Table 4-18) were taken from USGS (1994 through 2008). Soda ash production and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-18: Soda Ash Production and Consumption (Gg)

Year	Production[a]	Consumption
1990	14,700	6,530
1995	16,500	6,500
2000	15,700	6,390
2005	17,000	6,200
2006	16,700	6,110
2007	17,200	5,940

[a] Soda ash produced from trona ore only.

Uncertainty

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. The primary source of uncertainty, however, results from the fact that emissions from soda ash consumption are dependent upon the type of processing employed by each end-use. Specific information characterizing the emissions from each end-use is limited. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-19. Soda Ash Production and Consumption CO_2 emissions were estimated to be between 3.8 and 4.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 4.1 Tg CO_2 Eq.

Planned Improvements

Future inventories are anticipated to estimate emissions from glass production and other use of carbonates. These inventories will extract soda ash consumed for glass production and other use of carbonates from the current soda ash consumption emission estimates and include them under those sources.

4.5. Ammonia Production (IPCC Source Category 2B1) and Urea Consumption

Emissions of CO_2 occur during the production of synthetic ammonia, primarily through the use of natural gas as a feedstock. The natural gas-based, naphtha-based, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. One N production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some plants the CO_2 produced is captured and used to produce urea. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions.

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts CH_4 to CO_2, carbon monoxide (CO), and H_2 in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2. The secondary reforming step converts the

Table 4-19: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production and Consumption	CO_2	4.1	3.8	4.4	-7%	+7%

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

remaining CH_4 feedstock to CO and CO_2. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air in the shift conversion step. Carbon dioxide is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released.

The conversion process for conventional steam reforming of CH_4, including primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \xrightarrow{\text{(catalyst)}} 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced in the production of ammonia is emitted directly to the atmosphere. Both ammonia and CO_2 are used as raw materials in the production of urea [$CO(NH_2)_2$], which is another type of nitrogenous fertilizer that contains C as well as N. The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Urea is consumed for a variety of uses, including as a nitrogenous fertilizer, in urea-formaldehyde resins, and as a deicing agent (TIG 2002). The C in the consumed urea is assumed to be released into the environment as CO_2 during use. Therefore, the CO_2 produced by ammonia production that is subsequently used in the production of urea is still emitted during urea consumption. The majority of CO_2 emissions associated with urea consumption are those that result from its use as a fertilizer. These emissions are accounted for in the Cropland Remaining Cropland section of the Land Use, Land-Use Change, and Forestry chapter. Carbon dioxide emissions associated with other uses of urea are accounted for in this chapter. Net emissions of CO_2 from ammonia production in 2007 were 13.8 Tg CO_2 Eq. (13,786 Gg), and are summarized in Table 4-20 and Table 4-21. Emissions of CO_2 from urea consumed for non-fertilizer purposes in 2007 totaled 4.7 Tg CO_2 Eq. (4,750 Gg), and are summarized in Table 4-20 and Table 4-21. The decrease in ammonia production in recent years is due to several factors, including market fluctuations and high natural gas prices. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, domestic producers are competing with imports from countries with lower gas prices. If natural gas prices remain high, it is likely that domestically

Table 4-20: CO_2 Emissions from Ammonia Production and Urea Consumption (Tg CO_2 Eq.)

Source	1990	1995	2000	2005	2006	2007
Ammonia Production	13.0	13.5	12.2	9.2	8.8	9.0
Urea Consumption[a]	3.8	4.3	4.2	3.7	3.5	4.7
Total	**16.8**	**17.8**	**16.4**	**12.8**	**12.3**	**13.8**

[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.
Note: Totals may not sum due to independent rounding.

Table 4-21: CO_2 Emissions from Ammonia Production and Urea Consumption (Gg)

Source	1990	1995	2000	2005	2006	2007
Ammonia Production	13,047	13,541	12,172	9,196	8,781	9,036
Urea Consumption[a]	3,784	4,255	4,231	3,653	3,519	4,750
Total	**16,831**	**17,796**	**16,402**	**12,849**	**12,300**	**13,786**

[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.
Note: Totals may not sum due to independent rounding.

produced ammonia will continue to decrease with increasing ammonia imports (EEA 2004).

Methodology

The calculation methodology for non-combustion CO_2 emissions from production of nitrogenous fertilizers from natural gas feedstock is based on a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA). The selected EFMA factor is based on ammonia production technologies that are similar to those employed in the U.S. The CO_2 emission factor (1.2 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from natural gas feedstock. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. For each ton of urea produced, 8.8 of every 12 tons of CO_2 are consumed and 6.8 of every 12 tons of ammonia are consumed (European Fertilizer Manufacturers Association 2000). The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production. Total CO_2 emissions resulting from nitrogenous fertilizer production do not change as a result of this calculation, but some of the CO_2 emissions are attributed to ammonia production and some of the CO_2 emissions are attributed to urea consumption. Those CO_2 emissions that result from the use of urea as a fertilizer are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

The total amount of urea consumed for non-agricultural purposes 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 and is reported in Table 4-22, from the total U.S. production. Total urea production is estimated based on the amount of urea produced plus the sum of net urea imports and exports CO_2 emissions associated with urea that is used for non-fertilizer purposes are estimated using a factor of 0.73 tons of CO_2 per ton of urea consumed.

All 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. The CO_2 emission factor for production of ammonia from petroleum coke is based on plant specific data, wherein all C contained in the petroleum coke feedstock that is not used for urea production is assumed to be emitted to the atmosphere as CO_2 (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 CO_2 emission factor (3.57 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock.

The emission factor of 1.2 metric ton CO_2/metric ton NH_3 for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The

Table 4-22: Ammonia Production, Urea Production, Urea Net Imports, and Urea Exports (Gg)

Year	Ammonia Production	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	15,425	7,450	3,296	1,860	854
1995	15,788	7,370	3,623	2,936	881
2000	14,342	6,910	4,382	3,904	663
2005	10,143	5,270	4,779	5,026	536
2006	9,962	5,410	4,985	5,029	656
2007	10,386	5,630	5,389	6,546	310

EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO_2/metric ton NH_3, with 1.2 metric ton CO_2/metric ton NH_3 as a typical value. Technologies (e.g., catalytic reforming process) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. The emission factor of 3.57 metric ton CO_2/metric ton NH_3 for production of ammonia from petroleum coke feedstock was developed from plant-specific ammonia production data and petroleum coke feedstock utilization data for the ammonia plant located in Kansas (Bark 2004). As noted earlier, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Ammonia production data (see Table 4-22) was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2007) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Urea-ammonia nitrate production was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a). Urea production data for 1990 through 2007 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 1994 through 2007). Import data for urea were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for 1997 through 2007 (U.S. Census Bureau 1998 through 2007), 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 4-22). Urea export data for 1990 through 2007 were taken from U.S. Fertilizer Import/Exports from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2008).

Uncertainty

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 natural gas feedstock consumption data for the U.S. ammonia industry as a whole, 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. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material.

Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere.

Additional uncertainty is associated with the estimate of urea consumed for non-fertilizer purposes. Emissions associated with this consumption are reported in this source category, while those associated with consumption as fertilizer are reported in Cropland Remaining Cropland section of the Land Use, Land-Use Change, and Forestry chapter. The amount of urea used for non-fertilizer purposes is estimated based on estimates of urea production, net urea imports, and the amount of urea used as fertilizer. There is uncertainty associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-23. Ammonia Production and Urea Consumption CO_2 emissions were estimated to be between 12.1 and 15.2 Tg CO_2 Eq. at the 95 percent

Table 4-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production and Urea Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production and Urea Consumption	CO_2	13.8	12.1	15.2	-12%	+11%

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

confidence level. This indicates a range of approximately 12 percent below and 11 percent above the emission estimate of 13.8 Tg CO_2 Eq.

Recalculations Discussion

Urea export data were revised for 1990 through 2006 using the U.S. Department of Agriculture's Economic Research Service Data Set for U.S. Fertilizer Exports. These data were used because the previous data source discontinued publication of urea export data. On average, revisions to the exported urea dataset resulted in a decrease in annual emission estimates of less than one percent. Urea production data were revised for 1990 through 2006. These data were used in place of estimating urea production based on quantity of urea applied to agricultural lands and an estimated percent of urea consumed for agricultural purposes. On average, the new data resulted in a decrease in annual emission estimates of less than half of one percent.

Planned Improvements

Planned improvements to the Ammonia Production and Urea Consumption source category include updating emission factors to include both fuel and feedstock CO_2 emissions and incorporating CO_2 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. Additional efforts will be made to find consistent data sources for urea consumption and to report emissions from this consumption appropriately as defined by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

4.6. Nitric Acid Production (IPCC Source Category 2B2)

Nitric acid (HNO_3) is 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 catalytic oxidation of ammonia (EPA 1997). During this reaction, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere.

Table 4-24: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	20.0	64
1995	22.3	72
2000	21.9	71
2005	18.6	60
2006	18.2	59
2007	21.7	70

Currently, the nitric acid industry controls for emissions of NO and NO_2 (i.e., NO_x). As such, the industry 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. NSCRs were widely installed in nitric plants built between 1971 and 1977. Less than 5 percent of nitric acid plants use NSCR and they represent 0.6 percent of estimated national production (EPA 2008). The remaining 95 percent of the facilities use SCR or extended absorption, neither of which is known to reduce N_2O emissions.

Nitrous oxide emissions from this source were estimated to be 21.7 Tg CO_2 Eq. (70 Gg) in 2007 (see Table 4-24). Emissions from nitric acid production have increased by 8.5 percent since 1990, with the trend in the time series closely tracking the changes in production. Emissions increased 19 percent between 2006 and 2007, which resulted from an increase in nitric acid production driven by increased synthetic fertilizer demand by farmers taking advantage of high grain prices by expanding crop planting (ICIS 2008). Emissions have decreased by 8.8 percent since 1997, the highest year of production in the time series.

Methodology

Nitrous oxide emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emission factor was determined as a weighted average of 2 kg N_2O / metric ton HNO_3

Table 4-25: Nitric Acid Production (Gg)

Year	Gg
1990	7,195
1995	8,019
2000	7,900
2005	6,711
2006	6,573
2007	7,823

produced at plants using non-selective catalytic reduction (NSCR) systems and 9 kg N_2O/metric ton HNO_3 produced at plants not equipped with NSCR (IPCC 2006). In the process of destroying NO_x, NSCR systems destroy 80 to 90 percent of the N_2O, which is accounted for in the emission factor of 2 kg N_2O/metric ton HNO_3. Less than 5 percent of HNO_3 plants in the United States are equipped with NSCR representing 0.6 percent of estimated national production (EPA 2008). Hence, the emission factor is equal to $(9 \times 0.994) + (2 \times 0.006) = 9.0$ kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 through 2002 were obtained from the U.S. Census Bureau Current Industrial Reports (2006), and for 2003 through 2007 from the U.S. Census Bureau Current Industrial Reports (2008) (see Table 4-25).

Uncertainty

The overall uncertainty associated with the 2007 N_2O emissions estimate from nitric acid production was calculated using the *IPCC Guidelines for National Greenhouse Gas Inventories* (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of production data, the share of U.S. nitric acid production attributable to each emission abatement technology, and the emission factors applied to each abatement technology type.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-26. Nitrous oxide emissions from nitric acid production were estimated to be between 12.7 and 31.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 42 percent below to 44 percent above the 2007 emissions estimate of 21.7 Tg CO_2 Eq.

Recalculations Discussion

Changes to the weighted N_2O emission factor resulted in an increase in emissions across the time series. The weighted N_2O emission factor was previously based on the percentage of facilities equipped and not equipped with NSCR systems. The emission factor used for the current estimate is based on the percentage of HNO_3 produced at plants with NCSR systems and HNO_3 produced at plants without NSCR systems. Additionally, the nitric acid production value for 2006 has also been updated relative to the previous Inventory based on revised production data published by the U.S. Census Bureau (2008). Revised production data reduced emissions for 2006 by 0.2 Tg CO_2 Eq. (1.0 percent). Overall, these changes resulted in an average annual increase in N_2O emissions of 3.1 Tg CO_2 Eq. (17.8 percent) for the period 1990 through 2006 relative to the previous Inventory.

4.7. Adipic Acid Production (IPCC Source Category 2B3)

Adipic acid production is an anthropogenic source of N_2O emissions. Worldwide, few adipic acid plants exist. The United States and Europe are the major producers.

Table 4-26: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	21.7	12.7	31.3	-42%	+44%

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

The United States has three companies in four locations accounting for 34 percent of world production, and eight European producers account for a combined 38 percent of world production (CW 2007). 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).

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. 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). 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 of the three major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, the three major adipic acid production facilities had control systems in place (Reimer et al. 1999).[11] Only one small plant, representing approximately two percent of production, does not control for N_2O (ICIS 2007; VA DEQ 2006).

Nitrous oxide emissions from adipic acid production were estimated to be 5.9 Tg CO_2 Eq. (19 Gg) in 2007 (see Table 4-27). National adipic acid production has increased by approximately 26 percent over the period of 1990 through 2007, to approximately one million metric tons. Over the same period, emissions have been reduced by 61 percent due to the widespread installation of pollution control measures in the late 1990s.

Table 4-27: N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	15.3	49
1995	17.3	56
2000	6.2	20
2005	5.9	19
2006	5.9	19
2007	5.9	19

Methodology

For two production plants, 1990 to 2002 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 (Childs 2002, 2003). These estimates were based on continuous emissions monitoring equipment installed at the two facilities. Reported emission estimates for 2003 to 2007 were unavailable. Emission estimates for 2003 and 2004 were calculated by applying 4.4 and 4.2 percent national production growth rates, respectively. Emission estimates for 2005 to 2007 were kept the same as 2004. National production for 2003 was calculated through linear interpolation between 2002 and 2004 reported national production data. 2005 national production was calculated through linear interpolation between 2004 and 2006 reported national production. 2007 national production was kept the same as 2006. For the other two plants, N_2O emissions were calculated by multiplying adipic acid production by an emission factor (i.e., N_2O emitted per unit of adipic acid produced) and adjusting for the percentage of N_2O released as a result of plant-specific emission controls. On the basis of experiments, the overall reaction stoichiometry for N_2O production in the preparation of adipic acid was estimated at approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). Emissions are estimated using the following equation:

$$\begin{gathered}\text{N}_2\text{O emissions} = \{\text{production of adipic acid} \\ [\text{metric tons (MT) of adipic acid}]\} \times \\ (0.3 \text{ MT N}_2\text{O /MT adipic acid}) \times \\ [1\text{-}(\text{N}_2\text{O destruction factor} \times \text{abatement system utility factor})]\end{gathered}$$

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[11] During 1997, the N_2O emission controls installed by the third plant operated for approximately a quarter of the year.

The "N_2O destruction factor" 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. Overall, in the United States, two of the plants employ catalytic destruction, one plant employs thermal destruction, and the smallest plant uses no N_2O abatement equipment. For the one plant that uses thermal destruction and for which no reported plant-specific emissions are available, the N_2O abatement system destruction factor is assumed to be 98.5 percent, and the abatement system utility factor is assumed to be 97 percent (IPCC 2006).

For 1990 to 2003, plant-specific production data was estimated where direct emission measurements were not available. In order to calculate plant-specific production for the two plants, national adipic acid production was allocated to the plant level using the ratio of their known plant capacities to total national capacity for all U.S. plants. The estimated plant production for the two plants was then used for calculating emissions as described above. For 2004 and 2006, actual plant production data were obtained for these two plants and used for emission calculations. For 2005, interpolated national production was used for calculating emissions. For 2007, production was kept the same as 2006, as described above.

National adipic acid production data (see Table 4-28) for 1990 through 2002 were obtained from the American Chemistry Council (ACC 2003). Production for 2003 was estimated based on linear interpolation of 2002 and 2004 reported production. Production for 2004 and 2006 were obtained from *Chemical Week*, "Product Focus: Adipic Acid" (CW 2005, 2007). Plant capacities for 1990 through 1994 were obtained from *Chemical and 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 2005, the plant capacities for these three plants were kept the same as the year 2000 capacities. Plant capacity for 1999 to 2005 for the one remaining plant was kept the same as 1998. For 2004 to 2007, although plant capacity data are available (CW 1999, CMR 2001, ICIS 2007), they are not used to calculate plant-specific production for these years because plant-specific production data for 2004 and 2006 are also available and are used in our calculations instead (CW 2005, CW 2007).

Table 4-28: Adipic Acid Production (Gg)

Year	Gg
1990	735
1995	830
2000	925
2005	1,002
2006	1,002
2007	1,002

Uncertainty

The overall uncertainty associated with the 2007 N_2O emission estimate from adipic acid production was calculated using the *IPCC Guidelines for National Greenhouse Gas Inventories* (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of company specific production data, industry wide estimated production growth rates, emission factors for abated and unabated emissions, and company-specific historical emissions estimates.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-29. Nitrous oxide emissions from adipic acid production were estimated to be between 4.9 and 7.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below to 20 percent above the 2007 emission estimate of 5.9 Tg CO_2 Eq.

Planned Improvements

Improvement efforts will be focused on obtaining direct measurement data from facilities. If they become available,

Table 4-29: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	5.9	4.9	7.1	-18%	+20%

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

cross verification with top-down approaches will provide a useful Tier 2 level QC check. Also, additional information on the actual performance of the latest catalytic and thermal abatement equipment at plants with continuous emission monitoring may support the re-evaluation of current default abatement values.

4.8. Silicon Carbide Production (IPCC Source Category 2B4) and Consumption

Carbon dioxide and CH_4 are emitted from the production[12] of silicon carbide (SiC), a material used as an industrial abrasive. To make SiC, quartz (SiO_2) is reacted with C in the form of petroleum coke. A portion (about 35 percent) of the C contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or CO.

Carbon dioxide is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications. The 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 2005a).

Carbon dioxide emissions from SiC production and consumption in 2007 were 0.2 Tg CO_2 Eq. (196 Gg). Approximately 47 percent of these emissions resulted from SiC production while the remainder results from SiC consumption. CH_4 emissions from SiC production in 2007 were 0.01 Tg CO_2 Eq. CH_4 (0.4 Gg) (see Table 4-30 and Table 4-31).

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated by multiplying annual SiC production by the emission factors (2.62 metric tons CO_2/metric ton SiC

Table 4-30: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CO_2	0.4	0.3	0.2	0.2	0.2	0.2
CH_4	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 4-31: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Gas	1990	1995	2000	2005	2006	2007
CO_2	375	329	248	219	207	196
CH_4	1	1	1	+	+	+

+ Does not exceed 0.5 Gg.

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[12] Silicon carbide is produced for both abrasive and metallurgical applications in the United States. Production for metallurgical applications is not available and therefore both CH_4 and CO_2 estimates are based solely upon production estimates of silicon carbide for abrasive applications.

for CO_2 and 11.6 kg CH_4/metric ton SiC for CH_4) provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Emissions of CO_2 from silicon carbide consumption were 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 2005a). The total SiC consumed in metallurgical and other non-abrasive uses was multiplied by the C content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Production data for 1990 through 2007 were obtained from the *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2005a, 2006). Silicon carbide consumption by major end use was obtained from the *Minerals Yearbook: Silicon* (USGS 1991b through 2005b) (see Table 4-32) for years 1990 through 2004 and from the USGS Minerals Commodity Specialist for 2005 and 2006 (Corathers 2006, 2007). Silicon carbide consumption by major end use data for 2007 are proxied using 2006 data due to unavailability of data at time of publication. Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2008).

Table 4-32: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,465
1995	75,400	227,395
2000	45,000	225,070
2005	35,000	220,149
2006	35,000	199,937
2007	35,000	179,741

Uncertainty

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 CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also some uncertainty associated with production, net imports, and consumption data as well as the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-33. Silicon carbide production and consumption CO_2 emissions were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 Tg CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions

Table 4-33: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.18	0.22	-10%	+10%
Silicon Carbide Production	CH_4	+	+	+	-9%	+10%

+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg.
[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.01 Tg CO_2 Eq. at the 95 percent confidence level.

Recalculations Discussion

Estimates of CO_2 emissions from silicon carbide consumption were revised for all years due to the availability of more precise import and export data from the United States International Trade Commission. On average, these revisions resulted in a decrease in annual emissions of less than 1 percent.

Planned Improvements

Future improvements to the carbide production source category include continued research to determine if calcium carbide production and consumption data are available for the United States. If these data are available, calcium carbide emission estimates will be included in this source category.

4.9. Petrochemical Production (IPCC Source Category 2B5)

The production of some petrochemicals results in the release of small amounts of CH_4 and CO_2 emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. CH_4 emissions are presented here from the production of C black, ethylene, ethylene dichloride, and methanol, while CO_2 emissions are presented here for only C black production. The CO_2 emissions from petrochemical processes other than C black are currently included in the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels Section of the Energy chapter. The CO_2 from C black production is included here to allow for the direct reporting of CO_2 emissions from the process and direct accounting of the feedstocks used in the process.

Carbon black is an intense black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock. Most C 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. Ethylene 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. Ethylene dichloride is one of the first manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Methanol is an alternative transportation fuel as well as a principle ingredient in windshield wiper fluid, paints, solvents, refrigerants, and disinfectants. In addition, methanol-based acetic acid is used in making PET plastics and polyester fibers.

Emissions of CO_2 and CH_4 from petrochemical production in 2007 were 2.6 Tg CO_2 Eq. (2,636 Gg) and 1.0 Tg CO_2 Eq. (48 Gg), respectively (see Table 4-34 and Table 4-35), totaling 3.7 Tg CO_2 Eq. Emissions of CO_2 from C

Table 4-34: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CO_2	2.2	2.8	3.0	2.8	2.6	2.6
CH_4	0.9	1.1	1.2	1.1	1.0	1.0
Total	**3.1**	**3.8**	**4.2**	**3.9**	**3.6**	**3.7**

Table 4-35: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Gas	1990	1995	2000	2005	2006	2007
CO_2	2,221	2,750	3,004	2,804	2,573	2,636
CH_4	41	52	59	51	48	48

black production remained constant at 2.6 Tg CO_2 Eq. (2,573 Gg) in 2006 and 2007. There has been an overall increase in CO_2 emissions from C black production of 18 percent since 1990. CH_4 emissions from petrochemical production increased by approximately 17 percent since 1990.

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of chemical production by the appropriate emission factor, as follows: 11 kg CH_4/metric ton C black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[13] and 2 kg CH_4/metric ton methanol. Although the production of other chemicals may also result in CH_4 emissions, insufficient data were available to estimate their emissions.

Emission factors were taken from the Revised 1996 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997). Annual production data (see Table 4-36) were obtained from the American Chemistry Council's Guide to the Business of Chemistry (ACC 2002, 2003, 2005 through 2008) and the International Carbon Black Association (Johnson 2003, 2005 through 2008).

Almost all C black in the United States is produced from petroleum-based or coal-based feedstocks using the "furnace black" process (European IPPC Bureau 2004). The furnace black process is a partial combustion process in which a portion of the C black feedstock is combusted to provide energy to the process. C black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks ("acetylene black process") and by the thermal cracking of other hydrocarbons ("thermal black process"). One U.S. C black plant produces C black using the thermal black process, and one U.S. C black plant produces C black using the acetylene black process (The Innovation Group 2004).

The furnace black process produces C black from "C black feedstock" (also referred to as "C black oil"), which is a heavy aromatic oil that may be derived as a byproduct of either the petroleum refining process or the metallurgical (coal) coke production process. For the production of both petroleum-derived and coal-derived C black, the "primary feedstock" (i.e., C black feedstock) is injected into a furnace that is heated by a "secondary feedstock" (generally natural gas). Both the natural gas secondary feedstock and a portion of the C black feedstock are oxidized to provide heat to the production process and pyrolyze the remaining C black feedstock to C black. The "tail gas" from the furnace black process contains CO_2, carbon monoxide, sulfur compounds, CH_4, and non-CH_4 volatile organic compounds. A portion of the tail gas is generally burned for energy recovery to heat the downstream C black product dryers. The remaining tail gas may also be burned for energy recovery, flared, or vented uncontrolled to the atmosphere.

The calculation of the C lost during the production process is the basis for determining the amount of CO_2 released during the process. The C content of national C black production is subtracted from the total amount of C contained in primary and secondary C black feedstock to find the amount of C lost during the production process. It is assumed that the C lost in this process is emitted to the atmosphere as either CH_4 or CO_2. The C content of the CH_4 emissions, estimated as described above, is subtracted from the total C lost in the process to calculate the amount of C emitted as CO_2. The total amount of primary and secondary C black feedstock consumed in the process (see Table 4-37) is estimated using a primary feedstock consumption factor

Table 4-36: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1995	2000	2005	2006	2007
Carbon Black	1,307	1,619	1,769	1,651	1,515	1,552
Ethylene	16,541	21,214	24,970	23,954	25,000	25,392
Ethylene Dichloride	6,282	7,829	9,866	11,260	9,736	9,566
Methanol	3,785	4,992	5,221	2,336	1,123	1,068

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[13] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be ethylene dichloride ($C_2H_4Cl_2$) rather than dichloroethylene ($C_2H_2Cl_2$).

Table 4-37: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2005	2006	2007
Primary Feedstock	1,864	2,308	2,521	2,353	2,159	2,212
Secondary Feedstock	302	374	408	381	350	358

and a secondary feedstock consumption factor estimated from U.S. Census Bureau (1999 and 2004) data. The average C black feedstock consumption factor for U.S. C black production is 1.43 metric tons of C black feedstock consumed per metric ton of C black produced. The average natural gas consumption factor for U.S. C black production is 341 normal cubic meters of natural gas consumed per metric ton of C black produced. The amount of C contained in the primary and secondary feedstocks is calculated by applying the respective C contents of the feedstocks to the respective levels of feedstock consumption (EIA 2003, 2004).

For the purposes of emissions estimation, 100 percent of the primary C black feedstock is assumed to be derived from petroleum refining byproducts. C black feedstock derived from metallurgical (coal) coke production (e.g., creosote oil) is also used for C black production; however, no data are available concerning the annual consumption of coal-derived C black feedstock. C black feedstock derived from petroleum refining byproducts is assumed to be 89 percent elemental C (Srivastava et al. 1999). It is assumed that 100 percent of the tail gas produced from the C black production process is combusted and that none of the tail gas is vented to the atmosphere uncontrolled. The furnace black process is assumed to be the only process used for the production of C black because of the lack of data concerning the relatively small amount of C black produced using the acetylene black and thermal black processes. The C black produced from the furnace black process is assumed to be 97 percent elemental C (Othmer et al. 1992).

Uncertainty

The CH_4 emission factors used for petrochemical production are based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emission estimates; however, such data were not available. There may also be other significant sources of CH_4 arising from petrochemical production activities that have not been included in these estimates.

The results of the quantitative uncertainty analysis for the CO_2 emissions from C black production calculation are based on feedstock consumption, import and export data, and C black production data. The composition of C black feedstock varies depending upon the specific refinery production process, and therefore the assumption that C black feedstock is 89 percent C gives rise to uncertainty. Also, no data are available concerning the consumption of coal-derived C black feedstock, so CO_2 emissions from the utilization of coal-based feedstock are not included in the emission estimate. In addition, other data sources indicate that the amount of petroleum-based feedstock used in C black production may be underreported by the U.S. Census Bureau. Finally, the amount of C black produced from the thermal black process and acetylene black process, although estimated to be a small percentage of the total production, is not known. Therefore, there is some uncertainty associated with the assumption that all of the C black is produced using the furnace black process.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-38. Petrochemical production

Table 4-38: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Carbon Black Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	2.6	1.7	3.7	-34%	+40%
Petrochemical Production	CH_4	1.0	0.7	1.3	-31%	+31%

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

CO_2 emissions were estimated to be between 1.7 and 3.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 34 percent below to 40 percent above the emission estimate of 2.6 Tg CO_2 Eq. Petrochemical production CH_4 emissions were estimated to be between 0.7 and 1.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 31 percent below to 31 percent above the emission estimate of 1.0 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CH_4 emissions from petrochemical production were revised to account for small changes in ethylene, ethylene dichloride, and methanol production for years 1990 through 2006. On average, these revisions resulted in an annual increase in CH_4 emissions of approximately 1.5 percent.

Planned Improvements

Future improvements to the Petrochemical Production source category include research into the use of acrylonitrile in the United States, revisions to the C black CH_4 and CO_2 emission factors, and research into process and feedstock data to obtain Tier 2 emission estimates from the production of methanol, ethylene, propylene, ethylene dichloride, and ethylene oxide.

4.10. Titanium Dioxide Production (IPCC Source Category 2B5)

Titanium dioxide (TiO_2) is a metal oxide manufactured from titanium ore, and is principally used as a pigment. Titanium dioxide is a principal ingredient in white paint, and is also used as a pigment in the manufacture of white paper, foods, and other products. There are two processes for making TiO_2: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related CO_2. The sulfate process does not use petroleum coke or other forms of C as a raw material and does not emit CO_2.

The chloride process is based on the following chemical reactions:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

Table 4-39: CO_2 Emissions from Titanium Dioxide (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.2	1,195
1995	1.5	1,526
2000	1.8	1,752
2005	1.8	1,755
2006	1.9	1,876
2007	1.9	1,876

The C in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (the Ti-containing ore) to form CO_2. The majority of U.S. TiO_2 was produced in the United States through the chloride process, and a special grade of “calcined” petroleum coke is manufactured specifically for this purpose.

Emissions of CO_2 in 2007 were 1.9 Tg CO_2 Eq. (1,876 Gg), which represents an increase of 57 percent since 1990 (see Table 4-39).

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual TiO_2 production by chloride-process-specific emission factors.

Data were obtained for the total amount of TiO_2 produced each year. For years previous 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 had closed. As a result, all U.S. current TiO_2 production results from the chloride process (USGS 2005). An emission factor of 0.4 metric tons C/metric ton TiO_2 was applied to the estimated chloride-process production. It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other C inputs. The amount of petroleum coke consumed annually in TiO_2 production was calculated based on the assumption that the calcined petroleum coke used in the process is 98.4 percent C and 1.6 percent inert materials (Nelson 1969).

Table 4-40: Titanium Dioxide Production (Gg)

Year	Gg
1990	979
1995	1,250
2000	1,400
2005	1,310
2006	1,400
2007	1,400

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2006 (see Table 4-40) were obtained through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2008). Because 2007 production and capacity data were unavailable, 2006 production data were used. Percentage chloride-process data were not available for 1990 through 1993, and 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 plant remained online in the United States and this plant closed in 2004 (USGS 2005).

Uncertainty

Although some TiO_2 may be produced using graphite or other C inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated 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 TiO_2 produced, sufficient data were not available to do so.

Also, annual TiO_2 is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity by process is reported. The percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride 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. This assumes that the chloride-process plants and sulfate-process plants operate at the same level of utilization. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-41. Titanium dioxide consumption CO_2 emissions were estimated to be between 1.6 and 2.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Table 4-41: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.9	1.6	2.1	-12%	+13%

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

Planned Improvements

Future improvements to TiO_2 production methodology 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 estimates.

4.11. Carbon Dioxide Consumption (IPCC Source Category 2B5)

Carbon dioxide 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 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 used in industrial applications other than EOR is included in this analysis. Neither byproduct CO_2 generated from energy nor industrial production processes nor CO_2 separated from crude oil and natural gas are included in this analysis for a number of reasons. 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. Any CO_2 captured from industrial or energy production processes (e.g., ammonia plants, fossil fuel combustion) and used in non-EOR applications is assumed to be emitted to the atmosphere. The CO_2 emissions from such capture and use are therefore accounted for under Ammonia Production, Fossil Fuel Combustion, or other appropriate source category.[14]

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." The only CO_2 consumption that is accounted for in this analysis is CO_2 produced from naturally-occurring CO_2 reservoirs that is used in commercial applications other than EOR.

There are currently two facilities, one in Mississippi and one in New Mexico, producing CO_2 from naturally occurring CO_2 reservoirs for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). There are other naturally occurring CO_2 reservoirs, mostly located in the western United States. Facilities are producing CO_2 from these natural reservoirs, but they are only producing CO_2 for EOR applications, not for other commercial applications (Allis et al. 2000). Carbon dioxide production from these facilities is discussed in the Energy chapter.

In 2007, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere was 1.9 Tg CO_2 Eq. (1,867 Gg) (see Table 4-42). This amount represents an increase of 9 percent from the previous year and an increase

Table 4-42: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.4	1,416
1995	1.4	1,422
2000	1.4	1,421
2005	1.3	1,321
2006	1.7	1,709
2007	1.9	1,867

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[14] There are currently four known electric power plants operating in the United States that capture CO_2 for use as food-grade CO_2 or other industrial processes; however, insufficient data prevents estimating emissions from these activities as part of Carbon Dioxide Consumption.

of 32 percent since 1990. This increase was due to an increase in production at the Mississippi facility, despite the decrease in the percent of the facility's total reported production that was used for commercial applications.

Methodology

Carbon dioxide emission estimates for 1990 through 2007 were based on production data for the two facilities currently producing CO_2 from naturally-occurring CO_2 reservoirs for use in non-EOR applications. Some of the CO_2 produced by these facilities is used for EOR and some is used in other commercial applications (e.g., chemical manufacturing, food production). It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

Carbon dioxide production data for the Jackson Dome, Mississippi facility and the percentage of total production that was used for EOR and in non-EOR applications were obtained from the Advanced Resources Institute (ARI 2006, 2007) for 1990 to 2000 and from the Annual Reports for Denbury Resources (Denbury Resources 2002 through 2007) for 2001 to 2007 (see Table 4-43). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2007 and reported the percentage of the total average annual production that was used for EOR. Carbon dioxide production data for the Bravo Dome, New Mexico facility were obtained from the Advanced Resources International, Inc. (Godec 2008). The percentage of total production that was used for EOR and in non-EOR applications were obtained from the New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003 and New Mexico Bureau of Geology and Mineral Resources 2006).

Uncertainty

Uncertainty is associated with the number of facilities that are currently producing CO_2 from naturally occurring CO_2 reservoirs for commercial uses other than EOR, and for which the CO_2 emissions are not accounted for elsewhere. Research indicates that there are only two such facilities, which are in New Mexico and Mississippi; however, additional facilities may exist that have not been identified. In addition, it is possible that CO_2 recovery exists in particular production and end-use sectors that are not accounted for elsewhere. Such recovery may or may not affect the overall estimate of CO_2 emissions from that sector depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether CO_2 is being recovered from other facilities for application to end uses that are not accounted for elsewhere.

Table 4-43: CO_2 Production (Gg CO_2) and the Percent Used for Non-EOR Applications for Jackson Dome and Bravo Dome

Year	Jackson Dome CO_2 Production (Gg)	Jackson Dome % Used for Non-EOR	Bravo Dome CO_2 Production (Gg)	Bravo Dome % Used for Non-EOR
1990	1,353	100%	6,301	1%
1995	1,353	100%	6,862	1%
2000	1,353	100%	6,834	1%
2005	4,677	27%	5,799	1%
2006	6,610	25%	5,613	1%
2007	9,529	19%	5,605	1%

Table 4-44: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	1.9	1.5	2.3	-18%	+22%

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

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-44. Carbon dioxide consumption CO_2 emissions were estimated to be between 1.5 and 2.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below to 22 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from CO_2 Consumption have been revised for 2006 based on revised CO_2 production data from Jackson Dome. The revision resulted in an increase in emissions of approximately 8 percent for 2006.

Planned Improvements

Future improvements to the Carbon Dioxide Consumption source category include research into CO_2 capture for industrial purposes at electric power plants. Currently, four plants have been identified that capture CO_2 for these purposes, but insufficient data prevents including them in the current emission estimate.

4.12. Phosphoric Acid Production (IPCC Source Category 2B5)

Phosphoric acid (H_3PO_4) is a basic raw material in the production of phosphate-based fertilizers. Phosphate rock is mined in Florida, North Carolina, Idaho, Utah, and other areas of the United States and is used primarily as a raw material for phosphoric acid production. The production of phosphoric acid from phosphate rock produces byproduct gypsum ($CaSO_4 \bullet 2H_2O$), referred to as phosphogypsum.

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 C in the form of calcium carbonate (limestone) and also may contain organic C. The chemical composition of phosphate rock (francolite) mined in Florida is:

$$Ca_{10-x-y}\ Na_x\ Mg_y\ (PO_4)_{6-x}(CO_3)_xF_{2+0.4x}$$

The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic C that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry. Phosphoric acid production from natural phosphate rock is a source of CO_2 emissions, due to the chemical reaction of the inorganic C (calcium carbonate) component of the phosphate rock.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). The primary chemical reactions for the production of phosphoric acid from phosphate rock are:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow 3CaSO_4 \bullet 6H_2O + 6H_3PO_4$$

The limestone ($CaCO_3$) component of the phosphate rock reacts with the sulfuric acid in the phosphoric acid production process to produce calcium sulfate (phosphogypsum) and CO_2. The chemical reaction for the limestone-sulfuric acid reaction is:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$

Total marketable phosphate rock production in 2007 was 29.7 million metric tons. Approximately 87 percent of domestic phosphate rock production was mined in Florida and North Carolina, while approximately 13 percent of

Table 4-45: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
1995	1.5	1,513
2000	1.4	1,382
2005	1.4	1,386
2006	1.2	1,167
2007	1.2	1,166

production was mined in Idaho and Utah. In addition, 2.7 million metric tons of crude phosphate rock was imported for consumption in 2007. The vast majority, 99 percent, of imported phosphate rock is sourced from Morocco (USGS 2005). Marketable phosphate rock production, including domestic production and imports for consumption, decreased by less than 1 percent between 2006 and 2007. However, over the 1990 to 2007 period, production has decreased by 26 percent. Total CO_2 emissions from phosphoric acid production were 1.2 Tg CO_2 Eq. (1,166 Gg) in 2007 (see Table 4-45).

Methodology

Carbon dioxide emissions from production of phosphoric acid from phosphate rock are calculated by multiplying the average amount of calcium carbonate contained in the natural phosphate rock by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption.

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product.

From 1993 to 2004, the USGS *Minerals 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 4-46). For the years 1990, 1991, 1992, 2005, 2006, and 2007 only nationally aggregated mining data was reported by USGS. For these years, the breakdown of phosphate rock mined in Florida and North Carolina, and the amount mined in Idaho and Utah, are approximated using 1993 to 2004 data. Data for domestic production of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2007 were obtained from USGS *Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2008). From 2004-2007, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2008).

Table 4-46: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location	1990	1995	2000	2005	2006	2007
U.S. Production[a]	49,800	43,720	37,370	36,100	30,100	29,700
Florida & North Carolina	42,494	38,100	31,900	31,227	26,037	25,691
Idaho & Utah	7,306	5,620	5,470	4,874	4,064	4,010
Exports—Florida & North Carolina	6,240	2,760	299	–	–	–
Imports—Morocco	451	1,800	1,930	2,630	2,420	2,670
Total U.S. Consumption	**44,011**	**42,760**	**39,001**	**38,730**	**32,520**	**32,370**

– Assumed equal to zero.

[a] USGS does not disaggregate production data regionally (Florida & North Carolina and Idaho & Utah) for 1990, 2005, 2006, and 2007. Data for those years are estimated based on the remaining time series distribution.

Table 4-47: 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	–	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

– Assumed equal to zero.
Source: FIPR (2003).

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 2003). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-47).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (87 percent of domestic production) and carbonate content data for phosphate rock mined in Morocco are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 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). Carbonate content data for uncalcined phosphate rock mined in Idaho and Utah (13 percent of domestic production) were not available, and carbonate content was therefore estimated from the carbonate content data for calcined phosphate rock mined in Idaho.

Uncertainty

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 2007. 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 2007 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 2007 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 CO_2 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. Another source of uncertainty is the disposition of the organic C content of the phosphate rock. A representative of the 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 2003a). Organic C is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic C in the phosphate rock into CO_2. However, according to the USGS, only one producer in

Table 4-48: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	1.2	1.0	1.4	-18%	+18%

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

Idaho is currently calcining phosphate rock, and no data were available concerning the annual production of this single producer (USGS 2005). For available years, total production of phosphate rock in Utah and Idaho combined amounts to approximately 13 percent of total domestic production on average (USGS 1994 through 2005).

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 CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions is based on the assumption that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic C content in phosphate rock, but none from the organic C content.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-48. Phosphoric acid production CO_2 emissions were estimated to be between 1.0 and 1.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 18 percent above the emission estimate of 1.2 Tg CO_2 Eq.

Planned Improvements

Currently, data sources for the carbonate content of the phosphate rock are limited. If additional data sources are found, this information will be incorporated into future estimates.

4.13. Iron and Steel Production (IPCC Source Category 2C1) and Metallurgical Coke Production

The production of iron and steel is an energy-intensive process that also generates process-related emissions of CO_2 and CH_4. Metallurgical coke, which is manufactured using coking coal as a raw material, is used widely during the production of iron and steel. According to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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, so emissions from these are reported separately. Emission estimates presented in this chapter are based on the methodologies provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), which 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. The methodologies also call for reporting emissions from metallurgical coke production in the Energy sector; however, the approaches and emission estimates for both metallurgical coke production and iron and steel production are presented separately here because the activity data used to estimate emissions from metallurgical coke production have significant overlap with activity data used to estimate iron and steel production emissions. Further, 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 to point of consumption. As an example, CO_2 emissions associated with the combustion of coke oven gas in the blast furnace during pig iron production are attributed to pig iron production. Emissions associated with fuel consumption downstream of the iron and steelmaking furnaces, such as natural gas used for heating and annealing purposes, are reported in the Energy chapter.

The production of metallurgical coke from coking coal occurs both on-site at "integrated" iron and steel plants and off-site at "merchant" coke plants. Metallurgical coke is produced by heating coking coal in a coke oven in a low-oxygen environment. The process drives off the volatile components of the coking coal and produces coal (metallurgical) coke. Carbon-containing byproducts of the metallurgical coke manufacturing process include coke oven gas, coal tar, coke breeze (small-grade coke oven coke with particle size <5mm). Coke oven gas is recovered and used for underfiring the coke ovens and within the iron and steel mill. Small amounts of coke oven gas are also sold as synthetic natural gas outside of the iron and steel mills and are accounted for in the Energy chapter. Coal tar is used as a raw material to produce anodes used for primary aluminum production, electric arc furnace (EAF) steel production, and other electrolytic processes, and also used in the production of other coal tar products. Light oil is sold to petroleum refiners who use the material as an additive for gasoline. The metallurgical coke production process produces CO_2 emissions and fugitive CH_4 emissions.

Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure or crude iron containing about 3 to 5 percent carbon by weight). Inputs to the blast furnace include natural gas, fuel oil, and coke oven gas. The carbon in the metallurgical coke used in the blast furnace combines with oxides in the iron ore in a reducing atmosphere to produce blast furnace gas containing carbon monoxide (CO) and CO_2. The CO is then converted and emitted as CO_2 when combusted to either pre-heat the blast air used in the blast furnace or for other purposes at the steel mill. Iron may be introduced into the blast furnace in the form of raw iron ore, pellets (9-16mm iron-containing spheres), briquettes, or sinter. Pig iron is used as a raw material in the production of steel, which contains about 1 percent carbon by weight. Pig iron is also used as a raw material in the production of iron products in foundries. The pig iron production process produces CO_2 emissions and fugitive CH_4 emissions.

Iron can also be produced through the direct reduction process; wherein, iron ore is reduced to metallic iron in the solid state at process temperatures less than 1000°C. Direct reduced iron production results in process emissions of CO_2 and emissions of CH_4 through the consumption of natural gas used during the reduction process.

Sintering is a thermal process by which fine iron-bearing particles, such as air emission control system dust, are baked, which causes the material to agglomerate into roughly one-inch pellets that are then recharged into the blast furnace for pig iron production. Iron ore particles may also be formed into larger pellets or briquettes by mechanical means, and then agglomerated by heating. The agglomerate is then crushed and screened to produce an iron-bearing feed that is charged into the blast furnace. The sintering process produces CO_2 and fugitive CH_4 emissions through the consumption of carbonaceous inputs (e.g., coke breeze) during the sintering process.

Steel is produced from pig iron in a variety of specialized steel-making furnaces, including EAFs and basic oxygen furnaces (BOFs). Carbon inputs to steel-making furnaces include pig iron and scrap steel as well as natural gas, fuel oil, and fluxes (e.g., limestone, dolomite). In a BOF, the carbon in iron and scrap steel combines with high-purity oxygen to reduce the carbon content of the metal to the amount desired for the specified grade of steel. EAFs use carbon electrodes, charge carbon and other materials (e.g., natural gas) to aid in melting metal inputs (primarily recycled scrap steel), which are refined and alloyed to produce the desired grade of steel. Carbon dioxide emissions occur in BOFs occur through the reduction process. In EAFs, CO_2 emissions result primarily from the consumption of carbon electrodes and also from the consumption of supplemental materials used to augment the melting process.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation.[15] Process byproducts sold for use as synthetic natural gas are deducted and reported in the Energy chapter. Emissions associated with natural gas and fuel oil consumption for these purposes are reported in the Energy chapter.

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts at the iron and steel mill, with smaller amounts evolving from the use of flux and from the removal of carbon from pig iron used to produce steel. Some carbon is also stored in the finished iron and steel products.

Metallurgical Coke Production

Emissions of CO_2 and CH_4 from metallurgical coke production in 2007 were 3.8 Tg CO_2 Eq. (3,806 Gg) and less than 0.05 Tg CO_2 Eq. (less than 0.5 Gg), respectively (see Table 4-49 and Table 4-50), totaling 3.8 Tg CO_2 Eq. Emissions increased in 2007, but have decreased overall since 1990. In 2007, domestic coke production decreased by 1.2 percent and has decreased overall since 1990. Coke production in 2007 was 22 percent lower than in 2000 and 41 percent below 1990. Overall, emissions from metallurgical coke production have declined by 31 percent (1.7 Tg CO_2 Eq.) from 1990 to 2007.

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2007 were 73.6 Tg CO_2 Eq. (73,564 Gg) and 0.7 Tg CO_2 Eq. (33.2 Gg), respectively (see Table 4-51, Table 4-52, Table 4-53, and Table 4-54), totaling 74.3 Tg CO_2 Eq. Emissions increased in 2007, but have decreased overall since 1990 due to restructuring of the industry, technological improvements, and increased scrap 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.

Table 4-49: CO_2 and CH_4 Emissions from Metallurgical Coke Production (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CO_2	5.5	5.0	4.4	3.8	3.7	3.8
CH_4	+	+	+	+	+	+
Total	**5.5**	**5.0**	**4.4**	**3.8**	**3.7**	**3.8**

+ Does not exceed 0.05 Tg CO_2 Eq.

Table 4-50: CO_2 and CH_4 Emissions from Metallurgical Coke Production (Gg)

Gas	1990	1995	2000	2005	2006	2007
CO_2	5,498	5,037	4,381	3,849	3,682	3,806
CH_4	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

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[15] Emissions resulting from fuel consumption for the generation of electricity are reported in the Energy chapter. Some integrated iron and steel mills have on-site electricity generation for which fuel is used. Data are not available concerning the amounts and types of fuels used in iron and steel mills to generate electricity. Therefore all of the fuel consumption reported at iron and steel mills is assumed to be used within the iron and steel mills for purposes other than electricity consumption, and the amounts of any fuels actually used to produce electricity at iron and steel mills are not subtracted from the electricity production emissions value used in the Energy chapter, therefore some double-counting of electricity-related CO_2 emissions may occur.

Table 4-51: CO_2 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Process	1990	1995	2000	2005	2006	2007
Sinter Production	2.4	2.5	2.2	1.7	1.4	1.4
Iron Production	47.9	38.8	33.8	19.6	24.0	26.9
Steel Production	14.7	15.9	14.8	14.0	14.4	14.3
Other Activities[a]	39.3	40.9	39.9	34.2	32.6	31.0
Total	**104.3**	**98.1**	**90.7**	**69.3**	**72.4**	**73.6**

[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 4-52: CO_2 Emissions from Iron and Steel Production (Gg)

Process	1990	1995	2000	2005	2006	2007
Sinter Production	2,448	2,512	2,158	1,663	1,418	1,383
Iron Production	47,886	38,791	33,808	19,576	24,026	26,948
Steel Production	14,672	15,925	14,837	13,950	14,392	14,270
Other Activities[a]	39,256	40,850	39,877	34,152	32,583	30,964
Total	**104,262**	**98,078**	**90,680**	**69,341**	**72,418**	**73,564**

[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 4-53: CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Process	1990	1995	2000	2005	2006	2007
Sinter Production	+	+	+	+	+	+
Iron Production	0.9	1.0	0.9	0.7	0.7	0.7
Total	**1.0**	**1.0**	**0.9**	**0.7**	**0.7**	**0.7**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-54: CH_4 Emissions from Iron and Steel Production (Gg)

Process	1990	1995	2000	2005	2006	2007
Sinter Production	0.9	0.9	0.7	0.6	0.5	0.5
Iron Production	44.7	45.8	43.1	33.5	34.1	32.7
Total	**45.6**	**46.7**	**43.8**	**34.1**	**34.6**	**33.2**

Note: Totals may not sum due to independent rounding.

In 2007, domestic production of pig iron decreased by 4 percent. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2007 was 24 percent lower than in 2000 and 26 percent below 1990. Carbon dioxide emissions from steel production have decreased by 3 percent (4 Tg CO_2 Eq.) since 1990. Overall, CO_2 emissions from iron and steel production have declined by 29 percent (30.7 Tg CO_2 Eq.) from 1990 to 2007.

Methodology

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical (coal) 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 lead and zinc (see Lead Production and Zinc Production in 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 emission from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (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, 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 4-55).

Table 4-55: 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.

Table 4-56: CH_4 Emission Factor for Metallurgical Coke Production (g CH_4/metric ton)

Material Produced	g CH_4/metric ton
Metallurgical Coke	0.1

Source: IPCC (2006), Table 4.2.

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. 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.

The production processes for metallurgical coke production results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying the Tier 1 emission factor (0.1 g CH_4/metric ton) taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) for metallurgical coke production (see Table 4-56).

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 2004a) and January through March (EIA 2006a, 2007, 2008a) (see Table 4-57). 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 2008a) and through personal communications with AISI (2008b) (see

Table 4-57: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	1995	2000	2005	2006	2007
Metallurgical Coke Production						
Coking Coal Consumption at Coke Plants	35,269	29,948	26,254	21,259	20,827	20,607
Coke Production at Coke Plants	25,054	21,545	18,877	15,167	14,882	14,698
Coal Tar Production	752	646	566	455	446	441
Coke Breeze Production	1,879	1,616	1,416	1,138	1,116	1,102

Table 4-58: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (million ft^3)

Source/Activity Data	1990	1995	2000	2005	2006	2007
Metallurgical Coke Production						
Coke Oven Gas Production[a]	250,767	166,750	149,477	114,213	114,386	109,912
Natural Gas Consumption	599	184	180	2,996	3,277	3,309
Blast Furnace Gas Consumption	24,602	29,423	26,075	4,460	5,505	5,144

[a] Includes coke oven gas used for purposes other than coke oven underfiring only.

Table 4-58). The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (2008b). 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 for National Greenhouse Gas Inventories* (IPCC 2006). The carbon content for coke breeze was assumed to equal the carbon content of coke.

Iron and Steel Production

Emissions of CO_2 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 CO_2 emission factors (see Table 4-59). Because estimates of sinter production and direct reduced iron production were not available, production was assumed to equal consumption.

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, direct coal injection). The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-60). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process.

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 carbon 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 4-60). 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 2008b)). The amount of flux (e.g., limestone and dolomite) used during

Table 4-59: CO_2 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.

Table 4-60: 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.

steel manufacture was deducted from the Limestone and Dolomite Use 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 C content (see Table 4-60).

Carbon dioxide emissions associated with the sinter production, direct reduced iron production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-51 and Table 4-52).

The production processes for sinter and pig iron result in fugitive emissions of CH_4, which are emitted via leaks in the production equipment rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) for sinter production and the *1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 4-61) for pig iron production. The production of direct reduced iron also results in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas); however, these emissions estimates are excluded due to data limitations.

Table 4-61: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Pig Iron	0.9	g CH_4/kg
Sinter	0.07	kg CH_4/metric ton

Source: Sinter (IPCC 2006, Table 4.2), Pig Iron (IPCC/UNEP/OECD/IEA 1995, Table 2.2).

Sinter consumption and direct reduced iron consumption data were obtained from AISI's Annual Statistical Report (AISI 2004 through 2008a) and through personal communications with AISI (2008b) (see Table 4-62). Data on direct reduced iron consumed in EAFs were not available for the years 1990, 1991, 1999, 2006, and 2007. EAF direct reduced iron consumption in 1990 and 1991 was assumed to equal consumption in 1992, consumption in 1999 was assumed to equal the average of 1998 and 2000, and consumption in 2006 and 2007 was assumed to equal consumption in 2005. Data on direct reduced iron consumed in BOFs were not available for the years 1990 through 1994, 1999, 2006, and 2007. BOF direct reduced iron consumption in 1990 through 1994 was assumed to equal consumption in 1995, consumption in 1999 was assumed to equal the average of 1998 and 2000, and consumption in 2006 and 2007 was assumed to equal consumption in 2005. The Tier 1 CO_2 emission factors for sinter production and direct reduced iron production were obtained through the *2006 IPCC*

Table 4-62: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	1995	2000	2005	2006	2007
Sinter Production						
Sinter Production	12,239	12,562	10,788	8,315	7,088	6,914
Direct Reduced Iron Production						
Direct Reduced Iron Production	936	989	1,914	1,633	1,633	1,633
Pig Iron Production						
Coke Consumption	24,946	22,198	19,215	13,832	14,684	15,039
Pig Iron Production	49,669	50,891	47,888	37,222	37,904	36,337
Direct Injection Coal Consumption	1,485	1,509	3,012	2,573	2,526	2,734
EAF Steel Production						
EAF Anode and Charge Carbon Consumption	67	77	96	104	112	114
Scrap Steel Consumption	35,743	39,010	43,001	37,558	37,558	37,558
Flux Consumption	319	267	654	695	671	567
EAF Steel Production	33,511	38,472	47,860	52,194	56,071	57,004
BOF Steel Production						
Pig Iron Consumption	46,564	49,896	46,993	32,115	32,115	32,115
Scrap Steel Consumption	14,548	15,967	14,969	11,612	11,612	11,612
Flux Consumption	576	1,259	978	582	610	408
BOF Steel Production	43,973	56,721	53,965	42,705	42,119	41,099

Guidelines for National Greenhouse Gas Inventories (IPCC 2006). 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 2008a) and through personal communications with AISI (2008b) (see Table 4-63). Data for EAF steel production, flux, EAF charge carbon, direct reduced iron, pig iron, scrap steel, and natural gas consumption as well as EAF steel production were obtained from AISI's Annual Statistical Report (AISI 2004 through 2008a) and through personal communications with AISI (2008b). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (AISI 2008b). Data for BOF steel production, flux, direct reduced iron, pig iron, scrap steel, natural gas, natural ore, pellet sinter consumption as well as BOF steel production were obtained from AISI's Annual Statistical Report (AISI 2004 through 2008a) and through personal communications with AISI (2008b). Because data on pig iron consumption and scrap steel consumption in BOFs and EAFs were not available for 2006 and 2007, 2005 data were used. Because pig iron consumption in EAFs was also not available in 2003 and 2004, the average of 2002 and 2005 pig iron consumption data were used. 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 2008a) and through personal communications with AISI (2008b). Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained through EIA's Natural Gas Annual 2007 (EIA 2008b). C contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The C contents for natural gas, fuel oil, and direct injection coal as well as the heat contents for the same fuels were provided by EIA (2008b). Heat contents for coke oven gas and blast furnace gas were provided in Table 2-2 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000).

Uncertainty

The estimates of CO_2 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

Table 4-63: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (million ft^3 unless otherwise specified)

Source/Activity Data	1990	1995	2000	2005	2006	2007
Pig Iron Production						
Natural Gas Consumption	56,273	106,514	91,798	59,844	58,344	56,112
Fuel Oil Consumption (thousand gallons)	163,397	108,196	120,921	16,170	87,702	84,498
Coke Oven Gas Consumption	22,033	10,097	13,702	16,557	16,649	16,239
Blast Furnace Gas Production[a]	1,439,380	1,559,795	1,524,891	1,299,980	1,236,526	1,173,588
EAF Steel Production						
Natural Gas Consumption	9,604	11,026	13,717	14,959	16,070	16,337
BOF Steel Production						
Natural Gas Consumption	6,301	16,546	6,143	5,026	5,827	11,740
Coke Oven Gas Consumption	3,851	1,284	640	524	559	525
Other Activities						
Coke Oven Gas Consumption	224,883	155,369	135,135	97,132	97,178	93,148
Blast Furnace Gas Consumption	1,414,778	1,530,372	1,498,816	1,295,520	1,231,021	1,168,444

[a] Includes blast furnace gas used for purposes other than in the blast furnace only.

production because coal tar and coke breeze production data were not available.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. 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 carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon 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 timeseries. 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 (e.g., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions. However, there are uncertainties associated with each.

For the purposes of the CH_4 calculation it is assumed that all of the CH_4 escapes as fugitive emissions and that none of the CH_4 is captured in stacks or vents. Additionally, the CO_2 emissions calculation is not corrected by subtracting the C content of the CH_4, which means there may be a slight double counting of C as both CO_2 and CH_4.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-64 for iron and steel production. Iron and Steel Production CO_2 emissions were estimated to be between 57.0 and 87.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 22 percent below and 20 percent above the emission estimate of 73.6 Tg CO_2 Eq. Iron and Steel Production CH_4 emissions were estimated to be between 0.6 Tg CO_2 Eq. and 0.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 0.7 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 from iron and steel production have been revised for the years 1990 through 2006 to adhere to the methods presented in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Previously the estimates focused primarily on the consumption of coking coal to produce metallurgical coke and the consumption of metallurgical coke, carbon anodes, and scrap steel to produce iron and steel. The revised estimates differentiate between emissions associated with metallurgical coke production and those associated with iron and steel production and include CO_2 emissions from the consumption of other materials such as natural gas, fuel oil, flux (e.g. limestone and dolomite use), direction injection goal, sinter, pellets, and natural ore during the iron and steel production process as well as the metallurgical coke production process. Currently, CO_2 emissions from iron and steel production are reported separately from CO_2 emissions from metallurgical coke production. On average, revisions to the Iron and Steel Production estimate resulted in an annual increase of CO_2 emissions of 26.1 Tg CO_2 Eq. (40.7 percent).

Estimates of CH_4 emissions from iron and steel production have been revised based on revisions to the CH_4 emission factor from sinter production and to report

Table 4-64: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq. and Percent)[a]

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Iron and Steel Production	CO_2	73.6	57.0	87.9	-22%	+20%
Iron and Steel Production	CH_4	0.7	0.6	0.8	-8%	+8%

[a] The emission estimates and the uncertainty range presented in this table correspond to iron and steel production only. Uncertainty associated with emissions from metallurgical coke production were not estimated due to data limitations and were excluded from the uncertainty estimates presented in this table.

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

emissions from metallurgical coke production separately. On average, revisions to the Iron and Steel Production estimate resulted in an annual decrease of CH_4 emissions of 0.3 Tg CO_2 Eq. (24.6 percent).

Planned Improvements

Plans for improvements to the Iron and Steel Production source category include attributing emissions 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. Additional 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 inputs for preparing Tier 2 estimates for sinter and direct reduced iron production, as well as to identify information to better characterize emissions from the use of process gases and fuels within the Energy and Industrial Processes chapters.

4.14 Ferroalloy Production (IPCC Source Category 2C2)

Carbon dioxide and CH_4 are emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements such as silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Estimates from two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (about 98 percent silicon), and miscellaneous alloys (36 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. Consequently, government information disclosure rules prevent the publication of production data for these production facilities.

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced, and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the C contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Emissions of CO_2 from ferroalloy production in 2007 were 1.6 Tg CO_2 Eq. (1,552 Gg) (see Table 4-65 and Table 4-66), which is a 3 percent increase from the previous year and a 28 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2007 were 0.01 Tg CO_2 Eq. (0.448 Gg), which is also a 3 percent increase from the previous year and a 28 percent decrease since 1990.

Table 4-65: CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CO_2	2.2	2.0	1.9	1.4	1.5	1.6
CH_4	+	+	+	+	+	+
Total	**2.2**	**2.0**	**1.9**	**1.4**	**1.5**	**1.6**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 4-66: CO_2 and CH_4 Emissions from Ferroalloy Production (Gg)

Gas	1990	1995	2000	2005	2006	2007
CO_2	2,152	2,036	1,893	1,392	1,505	1,552
CH_4	1	1	1	+	+	+

+ Does not exceed 0.5 Gg.

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) were applied to ferroalloy production. For ferrosilicon alloys containing 25 to 55 percent silicon and miscellaneous alloys (including primarily magnesium-ferrosilicon, but also including other silicon alloys) containing 32 to 65 percent silicon, an emission factor for 45 percent silicon was applied for CO_2 (2.5 metric tons CO_2/metric ton of alloy produced) and an emission factor for 65 percent silicon was applied for CH_4 (1 kg CH_4/metric ton of alloy produced). Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon was applied for both CO_2 and CH_4 (4 metric tons CO_2/metric ton alloy produced and 1 kg CH_4/metric ton of alloy produced, respectively). The emission factors for silicon metal equaled 5 metric tons CO_2/metric ton metal produced and 1.2 kg CH_4/metric ton metal produced. It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke using an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite C inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent C and 10 percent inert material.

Ferroalloy production data for 1990 through 2007 (see Table 4-67) were obtained from the USGS through personal communications with the USGS Silicon Commodity Specialist (Corathers 2008) and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991 through 2007). Because USGS does not provide estimates of silicon metal production for 2006 and 2007, 2005 production data are used. Until 1999, the USGS reported production of ferrosilicon containing 25 to 55 percent silicon separately from production of miscellaneous alloys containing 32 to 65 percent silicon; beginning in 1999, the USGS reported these as a single category (see Table 4-67). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Uncertainty

Although some ferroalloys may be produced using wood or other biomass as a C source, 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 C is of biogenic origin.[16] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging

Table 4-67: 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
1995	184,000	128,000	163,000	99,500
2000	229,000	100,000	184,000	NA
2005	123,000	86,100	148,000	NA
2006	164,000	88,700	148,000	NA
2007	180,000	90,600	148,000	NA

NA (Not Available).

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[16] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Table 4-68: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.6	1.4	1.7	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

+ Does not exceed 0.05 Tg CO_2 Eq.

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

will reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

Also, annual ferroalloy production is now reported by the USGS in three broad categories: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal. It was assumed that the IPCC emission factors apply to all of the ferroalloy production processes, including miscellaneous alloys. Finally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing company proprietary data. Emissions from this production category, therefore, were not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-68. Ferroalloy production CO_2 emissions were estimated to be between 1.4 and 1.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.6 Tg CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 Tg CO_2 Eq.

Planned Improvements

Future improvements to the ferroalloy production source category include research into the data availability for ferroalloys other than ferrosilicon and silicon metal. If data are available, emissions will be estimated for those ferroalloys. Additionally, research will be conducted to determine whether data are available concerning raw material consumption (e.g., coal coke, limestone and dolomite flux, etc.) for inclusion in ferroalloy production emission estimates.

4.15 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 last reporting, the United States was the fourth largest producer of primary aluminum, with approximately seven percent of the world total (USGS 2008). 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 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 C lining that serves as the cathode. C 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 4.3 Tg CO_2 Eq. (4,251 Gg) in 2007 (see Table 4-69). 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

Table 4-69: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	6.8	6,831
1995	5.7	5,659
2000	6.1	6,086
2005	4.1	4,142
2006	3.8	3,801
2007	4.3	4,251

Table 4-70: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	15.9	2.7	18.5
1995	10.2	1.7	11.8
2000	7.8	0.8	8.6
2005	2.5	0.4	3.0
2006	2.1	0.4	2.5
2007	3.2	0.6	3.8

Note: Totals may not sum due to independent rounding.

Table 4-71: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.4	0.3
1995	1.6	0.2
2000	1.2	0.1
2005	0.4	+
2006	0.3	+
2007	0.5	0.1

+ Does not exceed 0.05 Gg.

for here rather than in the Iron and Steel source category of the Industrial Processes sector.

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 carbon 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 80 percent and 76 percent, respectively, to 3.2 Tg CO_2 Eq. of CF_4 (0.5 Gg) and 0.64 Tg CO_2 Eq. of C_2F_6 (0.07 Gg) in 2007, as shown in Table 4-70 and Table 4-71. 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. (Note, however, that production and the frequency and duration of anode effects increased in 2007 compared to 2006.) Since 1990, aluminum production has declined by 37 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 67 percent.

In 2007, U.S. primary aluminum production totaled approximately 2.6 million metric tons, a 12 percent increase from 2006 production levels. In December 2006, production resumed at the 265,000-t/y smelter in Hannibal, OH, owned by Ormet Corp (USGS 2007). In 2007, Columbia Falls Aluminum Co. announced it was restarting additional potlines (USAA 2007), and Alcoa Intalco Works reported increased production from a re-energized potline at their Ferndale operation (Alcoa Inc. 2007).

Methodology

Carbon dioxide emissions released during aluminum production were estimated using the combined application of process-specific emissions estimates modeling with individual partner reported data. These estimates are based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption; (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and /or following years, or; (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all carbon in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a carbon 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 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 CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, and 2007. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, and 13 out of 14 operating smelters in 2006 and 2007. For years where CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming industry default values.

In the absence of any smelter-specific process data (i.e., 1 out of 14 smelters in 2007 and 2006, 1 out of 15 smelters in 2005, and 5 out of 23 smelters between 1990 and 2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Aluminum production data for 13 out of 14 operating smelters were reported under the VAIP in 2007. Between 1990 and 2006, production data were provided 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 (USAA 2008), with allocation to specific smelters based on reported production capacities (USGS 2002).

PFC emissions from aluminum production were estimated using a per-unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration), as follows:

$$\text{PFC } (CF_4 \text{ or } C_2F_6) \text{ kg/metric ton Al} = S \times \text{Anode Effect Minutes/Cell-Day}$$

where,

S = Slope coefficient (kg PFC/metric ton Al)/(Anode Effect Minute/Cell-Day)

Anode Effect Minutes/Cell-Day = Anode Effect Frequency/Cell-Day × Anode Effect Duration (Minutes)

This approach corresponds to either the Tier 3 or the Tier 2 approach in the *2006 IPCC Guidelines*, depending upon whether the slope-coefficient is smelter-specific (Tier 3) or technology-specific (Tier 2). For 1990 through 2007, 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 2000, 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 2007, 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, 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 2007, 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.

National primary aluminum production data for 2007 were obtained via USAA (USAA 2008). For 1990 through 2001, and 2006 (see Table 4-72) data were obtained from USGS *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002, 2007). For 2002 through 2005, national aluminum production data were obtained from the United States Aluminum Association's *Primary Aluminum Statistics* (USAA 2004, 2005, 2006).

Table 4-72: Production of Primary Aluminum (Gg)

Year	Gg
1990	4,048
1995	3,375
2000	3,668
2005	2,478
2006	2,284
2007	2,560

Uncertainty

The overall uncertainties associated with the 2007 CO_2, CF_4, and C_2F_6 emission estimates were calculated using Approach 2, as defined by IPCC (2006). For CO_2, uncertainty was assigned to each of the parameters used to estimate CO_2 emissions. Uncertainty surrounding reported production data was assumed to be 1 percent (IPCC 2006). For additional variables, such as net C consumption, and sulfur and ash content in baked anodes, estimates for uncertainties associated with reported and default data were obtained from IPCC (2006). A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2 emission estimate for the U.S. aluminum industry as a whole, and the results are provided below.

To estimate the uncertainty associated with emissions of CF_4 and C_2F_6, the uncertainties associated with three variables were estimated for each smelter: (1) the quantity of aluminum produced; (2) the anode effect minutes per cell day (which may be reported directly or calculated as the product of anode effect frequency and anode effect duration); and (3) the smelter- or technology-specific slope coefficient. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emission estimate for each smelter and for the U.S. aluminum industry as a whole.

The results of this quantitative uncertainty analysis are summarized in Table 4-73. Aluminum production-related CO_2 emissions were estimated to be between 4.1 and 4.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 4 percent below to 4 percent above the emission estimate of 4.3 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 2.9 and 3.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below to 9 percent above the emission estimate of 3.2 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.5 and 0.8 Tg CO_2 Eq. at

Table 4-73: Tier 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	4.3	4.1	4.4	-4%	+4%
Aluminum Production	CF_4	3.2	2.9	3.5	-10%	+9%
Aluminum Production	C_2F_6	0.6	0.5	0.8	-27%	+32%

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

the 95 percent confidence level. This indicates a range of approximately 27 percent below to 32 percent above the emission estimate of 0.6 Tg CO_2 Eq.

The 2007 emission estimate was developed using site-specific PFC slope coefficients for all but 1 of the 14 operating smelters where default IPCC (2006) slope data was used.

This Inventory may slightly underestimate greenhouse gas emissions from aluminum production and casting because it does not account for the possible use of SF_6 as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. The extent of such use in the United States is not known. Historically, SF_6 emissions from aluminum activities have been omitted from estimates of global SF_6 emissions, with the explanation that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). The concentration of SF_6 in the mixtures is small and a portion of the SF_6 is decomposed in the process (MacNeal et al. 1990, Gariepy and Dube 1992, Ko et al. 1993, Ten Eyck and Lukens 1996, Zurecki 1996).

Recalculations Discussion

There were no recalculations in the historical timeseries for this source category.

4.16 Magnesium Production and Processing (IPCC Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. A dilute gaseous mixture of SF_6 with dry air and/or CO_2 is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF_6 reacting in magnesium production and processing is assumed to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty-five years.

The magnesium industry emitted 3.0 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2007, representing an increase of approximately 4 percent from 2006 emissions (see Table 4-74). The increase is attributed to higher production by the sand casting sector in 2007 (USGS 2008a). Counter to the increase in production from sand casting, a combination of high magnesium prices and reduced demand from the American auto industry has adversely impacted die casting operations in the United States (USGS 2008b).

Table 4-74: SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	5.4	0.2
1995	5.6	0.2
2000	3.0	0.1
2005	2.9	0.1
2006	2.9	0.1
2007	3.0	0.1

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. The Partnership started in 1999 and, currently, participating companies represent 100 percent of U.S. primary and secondary production and 90 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). Absolute emissions for 1999 through 2007 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which was assumed to be equivalent to emissions. When a partner did not report emissions, they were estimated based on the metal processed and emission rate reported by that partner in previous and (if available) subsequent years. Where data for subsequent years was not available, metal production and emissions rates were extrapolated based on the trend shown by partners reporting in the current and previous years.

Emission factors for 2002 to 2006 for sand casting activities were also acquired through the Partnership. For 2007, the sand casting partner did not report and the reported emission factor from 2005 was utilized as being representative of the industry. The 1999 through 2007 emissions from casting operations (other than die) were estimated by multiplying emission factors (kg SF_6 per metric ton of magnesium produced or processed) by the amount of metal produced or consumed. The emission factors for casting activities are provided below in Table 4-75. The emission factors for primary production, secondary production and sand casting are withheld to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 partner value of 1.1 kg SF_6 per metric ton.

Table 4-75: SF_6 Emission Factors (kg SF_6 per metric ton of Magnesium)

Year	Die Casting	Permanent Mold	Wrought	Anodes
1999	2.14[a]	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	0.81	2	1	1
2005	0.76	2	1	1
2006	0.86	2	1	1
2007	0.67	2	1	1

[a] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

Die casting emissions for 1999 through 2007, which accounted for 19 to 52 percent of all SF_6 emissions from the U.S. magnesium industry during this period, were estimated based on information supplied by industry partners. From 2000 to 2007, partners accounted for all U.S. die casting that was tracked by USGS. In 1999, 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. Die casters who were not partners were assumed to be similar to partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

Data used to develop SF_6 emission estimates were provided by the Magnesium Partnership participants and the USGS. U.S. magnesium metal production (primary and secondary) and consumption (casting) data from 1990 through 2007 were available from the USGS (USGS 2002, 2003, 2005, 2006, 2007, 2008a). Emission factors from 1990 through 1998 were based on a number of sources. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995, and an emission factor for die casting of 4.1 kg per metric ton was available for the mid-1990s from an international survey (Gjestland & Magers 1996).

To estimate emissions for 1990 through 1998, industry emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. The primary production emission factors were 1.2 kg per metric ton for 1990 through 1993, and 1.1 kg per metric ton for 1994 through 1997. For die casting, an emission factor of 4.1 kg per metric ton was used for the period 1990 through 1996. For 1996 through 1998, the emission factors for primary production and die casting were assumed to decline linearly to the level estimated based on partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that is reported in the RAND survey of major SF_6 manufacturers, which shows a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 2002 through 2007 were provided by the Magnesium Partnership participants, and 1990 through 2001 emission factors for this process were assumed to have been the same as the 2002 emission factor. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average partner value. 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 4-75.

Uncertainty

To estimate the uncertainty surrounding the estimated 2007 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated (1) emissions reported by magnesium producers and processors that participate in the SF_6 Emission Reduction Partnership; (2) emissions estimated for magnesium producers and processors that participate in the Partnership but did not report this year; and (3) emissions estimated for magnesium producers and processors that do not participate in the Partnership. An uncertainty of 5 percent was assigned to the data reported by each participant in the Partnership. If partners did not report emissions data during the current reporting year, SF_6 emissions data were estimated using available emission factors and production information reported in prior years; the extrapolation was based on the average trend for partners reporting in the current reporting year and the year prior. The uncertainty associated with the SF_6 usage estimate generated from the extrapolated emission factor and production information was estimated to be 30 percent; the lone sand casting partner did not report in the current reporting year and its activity and emission factor was held constant at 2006 and 2005 levels, respectively, and given an uncertainty of 30 percent. For those industry processes that are not represented in Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-75). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with sand casting activities utilized a partner-reported emission factor with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Recent measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-76. Sulfur hexafluoride emissions associated with magnesium production and processing were estimated to be between 2.6 and 3.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range

Table 4-76: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6	3.0	2.6	3.4	-12%	+13%

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

of approximately 12 percent below to 13 percent above the 2007 emission estimate of 3.0 Tg CO_2 Eq.

Recalculations Discussion

Newly reported historical data from a secondary remelt partner led to revised SF_6 emission estimates in the years 2001 to 2006; the new data resulted in an average decrease of 0.3 Tg CO_2 Eq. in emissions for the 2004 to 2006 period, or about 10 percent of total emissions.

Planned Improvements

As more work assessing the degree of cover gas degradation and associated byproducts is undertaken and published, results could potentially be used to refine the emission estimates, which currently assume (per the 2006 IPCC Guidelines, IPCC 2006) that all SF_6 utilized is emitted to the atmosphere. EPA-funded measurements of SF_6 in die casting applications have indicated that the latter assumption may be incorrect, with observed SF_6 degradation on the order of 20 percent (Bartos et al. 2007). Another issue that will be addressed in future inventories is the likely adoption of alternate cover gases by U.S. magnesium producers and processors. These cover gases, which include AM-cover™ (containing HFC-134a) and Novec™ 612, have lower GWPs than SF_6, and tend to quickly decompose during their exposure to the molten metal. Magnesium producers and processors have already begun using these cover gases for 2006 and 2007 in a limited fashion; because the amounts are currently negligible these emissions are only being monitored and recorded at this time.

4.17. Zinc Production (IPCC Source Category 2C5)

Zinc production in the United States consists of both primary and secondary processes. Primary production techniques used in the United States are the electrothermic and electrolytic process while secondary techniques used in the United States include a range of 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). Of the primary and secondary processes used in the United States, the electrothermic process results in non-energy CO_2 emissions, as does the Waelz Kiln process—a technique used to produce secondary zinc from electric-arc furnace (EAF) dust (Viklund-White 2000).

During the electrothermic zinc production process, roasted zinc concentrate and, when available, secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke added to the electric retort furnace reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process produces non-energy CO_2 emissions (Sjardin 2003). The electrolytic zinc production process does not produce non-energy CO_2 emissions.

In the Waelz Kiln process, EAF dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent—often metallurgical coke. When kiln temperatures reach approximately 1100–1200°C, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. Through this process, approximately 0.33 ton of zinc is produced for every ton of EAF dust treated (Viklund-White 2000).

In 2007, U.S. primary and secondary zinc production totaled 519,221 metric tons (Tokin 2009). The resulting emissions of CO_2 from zinc production in 2007 were estimated to be 0.5 Tg CO_2 Eq. (530 Gg) (see Table 4-77). All 2007 CO_2 emissions result from secondary zinc production.

After a gradual increase in total emissions from 1990 to 2000, largely due to an increase in secondary zinc production, emissions have decreased in recent years due to the closing of an electrothermic-process zinc plant in Monaca, PA (USGS

Table 4-77: CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.9	949
1995	1.0	1,013
2000	1.1	1,140
2005	0.5	465
2006	0.5	529
2007	0.5	530

2004). Emissions for 2007, which are nearly half that of 1990 (44 percent), remained constant from 2006 due to the use of proxied data for secondary zinc production.

Methodology

Non-energy CO_2 emissions from zinc production result from those processes that use metallurgical coke or other C-based materials as reductants. Sjardin (2003) provides an emission factor of 0.43 metric tons CO_2/ton zinc produced for emissive zinc production processes; however, this emission factor is based on the Imperial Smelting Furnace production process. Because the Imperial Smelting Furnace production process is not used in the United States, emission factors specific to those emissive zinc production processes used in the United States, which consist of the electrothermic and Waelz Kiln processes, were needed. Due to the limited amount of information available for these electrothermic processes, only Waelz Kiln process-specific emission factors were developed. These emission factors were applied to both the Waelz Kiln process and the electrothermic zinc production processes. A 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, 1.19 metric tons coke/metric ton zinc produced (Viklund-White 2000), and the following equation:

$$EF_{\text{Waelz Kiln}} = 1.19 \frac{\text{metric tons coke}}{\text{metric tons zinc}} \times 0.84 \frac{\text{metric tons C}}{\text{metric tons coke}} \times 3.67 \frac{\text{metric tons } CO_2}{\text{metric tons C}} = 3.66 \frac{\text{metric tons } CO_2}{\text{metric tons zinc}}$$

The USGS disaggregates total U.S. primary zinc production capacity into zinc produced using the electrothermic process and zinc produced using the electrolytic process; however, the USGS does not report the amount of zinc produced using each process, only the total zinc production capacity of the zinc plants using each process. The total electrothermic zinc production capacity is divided by total primary zinc production capacity to estimate the percent of primary zinc produced using the electrothermic process. This percent is then multiplied by total primary zinc production to estimate the amount of zinc produced using the electrothermic process, and the resulting value is multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for primary zinc production. According to the USGS, the only remaining plant producing primary zinc using the electrothermic process closed in 2003 (USGS 2004). Therefore, CO_2 emissions for primary zinc production are reported only for years 1990 through 2002.

In the United States, secondary zinc is produced through either the electrothermic or Waelz Kiln process. In 1997, the Horsehead Corporation plant, located in Monaca, PA, produced 47,174 metric tons of secondary zinc using the electrothermic process (Queneau et al. 1998). This is the only plant in the United States that uses the electrothermic process to produce secondary zinc, which, in 1997, accounted for 13 percent of total secondary zinc production. This percentage was applied to all years within the time series up until the Monaca plant's closure in 2003 (USGS 2004) to estimate the total amount of secondary zinc produced using the electrothermic process. This value is then multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for secondary zinc produced using the electrothermic process.

U.S. secondary zinc is also produced by processing recycled EAF dust in a Waelz Kiln furnace. Due to the complexities of recovering zinc from recycled EAF dust, an emission factor based on the amount of EAF dust consumed rather than the amount of secondary zinc produced is believed to represent actual CO_2 emissions from the process more accurately (Stuart 2005). An 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, 0.4 metric tons coke/metric ton EAF dust consumed (Viklund-White 2000), and the following equation:

$$EF_{\text{EAF Dust}} = 0.4 \frac{\text{metric tons coke}}{\text{metric tons EAF dust}} \times 0.84 \frac{\text{metric tons C}}{\text{metric tons coke}} \times 3.67 \frac{\text{metric tons } CO_2}{\text{metric tons C}} = 1.23 \frac{\text{metric tons } CO_2}{\text{metric tons EAF dust}}$$

Table 4-78: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	341,400
1995	231,840	353,000
2000	227,800	440,000
2005	191,120	349,000
2006	113,000	397,000
2007	121,221	398,000

The Horsehead Corporation plant, located in Palmerton, PA, is the only large plant in the United States that produces secondary zinc by recycling EAF dust (Stuart 2005). In 2003, this plant consumed 408,240 metric tons of EAF dust, producing 137,169 metric tons of secondary zinc (Recycling Today 2005). This zinc production accounted for 36 percent of total secondary zinc produced in 2003. This percentage was applied to the USGS data for total secondary zinc production for all years within the time series to estimate the total amount of secondary zinc produced by consuming recycled EAF dust in a Waelz Kiln furnace. This value is multiplied by the Waelz Kiln process emission factor for EAF dust to obtain total CO_2 emissions.

The 1990 through 2006 activity data for primary and secondary zinc production (see Table 4-78) were obtained through the USGS *Mineral Yearbook: Zinc* (USGS 1994 through 2008). Preliminary data for 2007 primary production and production from scrap were obtained from the USGS Mineral Commodity Specialist (Tolcin 2009). Because data for 2007 secondary zinc production were unavailable, 2006 data were used.

Uncertainty

The uncertainties contained in these estimates are two-fold, relating to activity data and emission factors used.

First, there are uncertainties associated with the percent of total zinc production, both primary and secondary, that is attributed to the electrothermic and Waelz Kiln emissive zinc production processes. For primary zinc production, the amount of zinc produced annually using the electrothermic process is estimated from the percent of primary zinc production capacity that electrothermic production capacity constitutes for each year of the time series. This assumes that each zinc plant is operating at the same percentage of total production capacity, which may not be the case and this calculation could either overestimate or underestimate the percentage of the total primary zinc production that is produced using the electrothermic process. The amount of secondary zinc produced using the electrothermic process is estimated from the percent of total secondary zinc production that this process accounted for during a single year, 2003. The amount of secondary zinc produced using the Waelz Kiln process is estimated from the percent of total secondary zinc production this process accounted for during a single year, 1997. This calculation could either overestimate or underestimate the percentage of the total secondary zinc production that is produced using the electrothermic or Waelz Kiln processes. Therefore, there is uncertainty associated with the fact that percents of total production data estimated from production capacity, rather than actual production data, are used for emission estimates.

Second, there are uncertainties associated with the emission factors used to estimate CO_2 emissions from the primary and secondary production processes. Because the only published emission factors are based on the Imperial Smelting Furnace, which is not used in the United States, country-specific emission factors were developed for the Waelz Kiln zinc production process. 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. Furthermore, the Waelz Kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed during zinc production provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-79. Zinc production CO_2

Table 4-79: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.5	0.4	0.7	-21%	+25%

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

emissions were estimated to be between 0.4 and 0.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 25 percent above the emission estimate of 0.5 Tg CO_2 Eq.

4.18. Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes—both of which emit CO_2 (Sjardin 2003). Primary lead production, in the form of direct smelting, mostly occurs at plants located in Alaska and Missouri, though to a lesser extent in Idaho, Montana, and Washington. Secondary production largely involves the recycling of lead acid batteries at approximately 18 separate smelters located in 11 states (USGS 2008 and 2009). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2007, secondary lead production accounted for approximately 91 percent of total lead production (USGS 2009).

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). U.S. primary lead production decreased by 20 percent from 2006 to 2007 and has decreased by 68 percent since 1990 (USGS 2009, USGS 1995).

At last reporting, approximately 93 percent of refined lead production is produced primarily from scrapped lead acid batteries (USGS 2009). Similar to primary lead production, CO_2 emissions result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process (Sjardin 2003). U.S. secondary lead production decreased from 2006 to 2007 by 2 percent, and has increased by 28 percent since 1990 (USGS 2009, USGS 1995).

At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for 12 percent of world production in 2007 (USGS 2009). In 2007, U.S. primary and secondary lead production totaled 1,303,000 metric tons (USGS 2009). The resulting emissions of CO_2 from 2007 production were estimated to be 0.3 Tg CO_2 Eq. (267 Gg) (see Table 4-80). The majority of 2007 lead production is from secondary processes, which account for 88 percent of total 2007 CO_2 emissions.

After a gradual increase in total emissions from 1990 to 2000, total emissions have decreased by six percent since 1990, largely due to a decrease in primary production (68 percent since 1990) and a transition within the United States from primary lead production to secondary lead production, which is less emissive than primary production, although the sharp decrease leveled off in 2005 (USGS 2009, Smith 2007).

Table 4-80: CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.3	285
1995	0.3	298
2000	0.3	311
2005	0.3	266
2006	0.3	270
2007	0.3	267

Table 4-81: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
1995	374,000	1,020,000
2000	341,000	1,130,000
2005	143,000	1,150,000
2006	153,000	1,160,000
2007	123,000	1,180,000

Methodology

Non-energy CO_2 emissions from lead production result from primary and secondary production processes that use metallurgical coke or other C-based materials as reductants. For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.2 metric tons CO_2/ton lead produced. Both factors are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The 1990 through 2007 activity data for primary and secondary lead production (see Table 4-81) were obtained through the USGS *Minerals Yearbook: Lead* (USGS 1994 through 2009).

Uncertainty

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 averages the values provided by three other studies (Dutrizac et al. 2000, Morris et al. 1983, Ullman 1997). For secondary production, Sjardin (2003) reduces this factor by 50 percent and adds a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-82. Lead production CO_2 emissions were estimated to be between 0.2 and 0.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 17 percent above the emission estimate of 0.3 Tg CO_2 Eq.

Table 4-82: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.3	0.2	0.3	-16%	+17%

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

4.19. HCFC-22 Production (IPCC Source Category 2E1)

Trifluoromethane (HFC-23 or CHF_3) is generated as a byproduct during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Since 2000, U.S. production has fluctuated but has generally remained above 1990 levels. 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.[17] Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Emissions of HFC-23 in 2007 were estimated to be 17.0 Tg CO_2 Eq. (1.5 Gg) (Table 4-83). This quantity represents a 23 percent increase from 2006 emissions and a 53 percent decline from 1990 emissions. The increase from 2006 emissions was caused by a 5 percent increase in HCFC-22 production and a 17 percent increase in the HFC-23 emission rate. The decline from 1990 emissions is due to a 60 percent decrease in the HFC-23 emission rate since 1990. The decrease is primarily attributable to four 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; and (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale. Three HCFC-22 production plants operated in the United States in 2008, two of which used thermal oxidation to significantly lower their HFC-23 emissions.

Table 4-83: HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	36.4	3
1995	33.0	3
2000	28.6	2
2005	15.8	1
2006	13.8	1
2007	17.0	1

Methodology

To estimate their emissions of HFC-23, five of the eight HCFC-22 plants that have operated in the U.S. since 1990 use (or, for those plants that have closed, used) methods comparable to the Tier 3 methods in the 2006 IPCC Guidelines (IPCC 2006). The other three plants, the last of which closed in 1993, used methods comparable to the Tier 1 method in the *2006 IPCC Guidelines*. Emissions from these three plants have been recalculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced). (This recalculation was reflected in the 1990 through 2006 inventory submission.)

The five plants that have operated since 1994 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.

In most years, including 2008, an industry association aggregates and reports to EPA country-level estimates of HCFC-22 production and HFC-23 emissions (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008). However, in 1997 and 2008, EPA (through a contractor) performed comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production (RTI 1997; RTI 2008). These reviews enabled EPA to review, update,

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[17] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer*. [42 U.S.C. §7671m(b), CAA §614].

Table 4-84: HCFC-22 Production (Gg)

Year	Gg
1990	139
1995	155
2000	186
2005	156
2006	154
2007	162

and where necessary, correct U.S. totals, and also to perform plant-level uncertainty analyses (Monte-Carlo simulations) for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-84.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo 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.

Because EPA did not have access to plant-level emissions data for 2007, the relative errors yielded by the Monte Carlo simulation for 2006 were applied to the U.S. emission estimate for 2007. The resulting estimates of absolute uncertainty are likely to be accurate because (1) the methods used by the three plants to estimate their emissions are not believed to have changed significantly since 2006; (2) the distribution of emissions among the plants is not believed to have changed significantly since 2006 (one plant continues to dominate emissions); and (3) the country-level relative errors yielded by the Monte Carlo simulations for 2005 and 2006 were very similar, implying that these errors are not sensitive to small, year-to-year changes.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-85. HFC-23 emissions from HCFC-22 production were estimated to be between 15.8 and 18.6 Tg CO_2 Eq. at the 95-percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 17.0 Tg CO_2 Eq.

Table 4-85: Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	17.0	15.8	18.6	-7%	+10%

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

4.20. 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*.[18] 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 4-86 and Table 4-87.

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[18] [42 U.S.C § 7671, CAA § 601].

Table 4-86: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
HFC-23	+	+	+	+	+	+
HFC-32	+	+	+	0.4	0.6	0.9
HFC-125	+	0.8	5.2	10.3	12.3	14.7
HFC-134a	+	25.4	57.2	70.5	70.7	68.6
HFC-143a	+	0.5	4.1	12.2	14.4	16.7
HFC-236fa	+	0.2	0.5	0.8	0.8	0.9
CF_4	+	+	+	+	+	+
Others[a]	0.3	1.6	4.0	5.9	6.2	6.5
Total	**0.3**	**28.5**	**71.2**	**100.0**	**105.0**	**108.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 4-87: Emissions of HFCs and PFCs from ODS Substitution (Mg)

Gas	1990	1995	2000	2005	2006	2007
HFC-23	+	+	1	1	1	1
HFC-32	+	+	44	562	913	1,325
HFC-125	+	291	1,873	3,675	4,394	5,253
HFC-134a	+	19,537	44,011	54,226	54,362	52,782
HFC-143a	+	132	1,089	3,200	3,782	4,402
HFC-236fa	+	36	85	125	131	136
CF_4	+	+	1	2	2	2
Others[a]	M	M	M	M	M	M

M (Mixture of Gases)

+ Does not exceed 0.5 Mg

[a] Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers—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.[19] In 1993, the use of HFCs in foam production began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased out.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 108.3 Tg CO_2 Eq. in 2007. 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 accelerate 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 4-88 presents HFCs and PFCs emissions by end-use sector for 1990 through 2007. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2007 include refrigeration and air-conditioning (97.5 Tg CO_2 Eq., or approximately 90 percent), aerosols (6.2 Tg CO_2 Eq., or approximately 6 percent), and foams (2.6 Tg CO_2 Eq., or approximately 2 percent). Within

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[19] R-404A contains HFC-125, HFC-143a, and HFC-134a.

Table 4-88: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO_2 Eq.) by Sector

Gas	1990	1995	2000	2005	2006	2007
Refrigeration/Air-conditioning	+	19.3	58.6	90.1	94.6	97.5
Aerosols	+	8.1	10.1	5.9	6.1	6.2
Foams	+	+	+	2.2	2.4	2.6
Solvents	+	0.9	2.1	1.3	1.3	1.3
Fire Protection	+	+	+	0.5	0.6	0.7
Total	**+**	**28.5**	**71.2**	**100.0**	**105.0**	**108.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (52.9 Tg CO_2 Eq.), followed by refrigerated transport and retail food. Each of the end-use sectors is described in more detail below.

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/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, R-404A, and R-507A. These HFCs 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 committed to replace the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but eventually, the industry expects to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. These propellants are released into the atmosphere as the aerosol products are used.

Foams

CFCs and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2, 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 foam, 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 is used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. 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

CFCs, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-4310mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and sale of 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-236ea 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, HFC-236fa, 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. As fire protection equipment is tested or deployed, emissions of these HFCs are released.

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 the model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. This 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 50 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 3.8.

Uncertainty

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 over 50 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 19 end-uses, comprising over 97 percent of the total emissions, and 5 other end-uses. 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. This year, two new end-uses were included in the uncertainty estimate—polyurethane flexible integral skin foam and residential unitary air conditioners. 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 97 percent of emissions from ODS Substitutes.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put

Table 4-89: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)[a]	Uncertainty Range Relative to Emission Estimate[b] ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	105.9	97.5	115.2	-8%	+9%

[a] 2007 Emission estimates and the uncertainty range presented in this table correspond to aerosols, foams, solvents, fire extinguishing agents, and refrigerants, but not for other remaining categories. Therefore, because the uncertainty associated with emissions from "other" ODS substitutes was not estimated, they were exclude in the estimates reported in this table.

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

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 mobile air-conditioning and refrigerated transport, as well as the percent of non-MDI aerosol propellant that is HFC-152a.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-89. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 97.5 and 115.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below to 9 percent above the emission estimate of 105.9 Tg CO_2 Eq.

Recalculations Discussion

An extensive review of the chemical substitution trends, market sizes, growth rates, and charge sizes, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model. These changes resulted in an average annual net decrease of 1.2 Tg CO_2 Eq. (1.2 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2007. The primary change was a revision in the non-MDI aerosol sector, where a fraction of the market formerly assumed to use HFC-134a (with a GWP of 1,300) was discovered to be transitioning more quickly to HFC-152a (with a GWP of 140).

4.21. Semiconductor Manufacture (IPCC Source Category 2F6)

The semiconductor industry uses multiple long-lived fluorinated 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 CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

A single 300 mm silicon wafer that yields between 400 to 500 semiconductor products (devices or chips) may require as many as 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 C_2F_6 is used in cleaning or etching, CF_4 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.

For 2007, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 4.7 Tg CO_2 Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-90 and Table 4-91 below for years 1990, 1995, 2000 and the period 2005 to 2007. The rapid growth of this industry and the increasing complexity (growing number of layers)[20] of semiconductor products led to an increase in emissions of 150 percent between 1990 and 1999, when emissions peaked at 7.2 Tg CO_2 Eq. The emissions growth rate began to slow after 1998, and emissions declined by 35 percent between 1999 and 2007. Together, industrial growth and adoption of emissions reduction technologies, including but not limited to abatement technologies, resulted in a net increase in emissions of 63 percent between 1990 and 2007.

Table 4-90: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CF_4	0.7	1.3	1.8	1.1	1.2	1.3
C_2F_6	1.5	2.5	3.0	2.0	2.2	2.3
C_3F_8	0.0	0.0	0.1	0.0	0.0	0.0
c-C_4F_8	0.0	0.0	0.0	0.1	0.1	0.1
HFC-23	0.2	0.3	0.3	0.2	0.3	0.3
SF_6	0.5	0.9	1.1	1.0	1.0	0.8
NF_3[a]	0.0	0.1	0.2	0.4	0.7	0.5
Total	**2.9**	**4.9**	**6.2**	**4.4**	**4.7**	**4.7**

[a] NF_3 emissions are presented for informational purposes, using the AR4 GWP of 17,200, and are not included in totals.
Note: Totals may not sum due to independent rounding.

Table 4-91: PFC, HFC, and SF_6 Emissions from Semiconductor Manufacture (Mg)

Gas	1990	1995	2000	2005	2006	2007
CF_4	115	193	281	168	181	195
C_2F_6	160	272	321	216	240	246
C_3F_8	0	0	18	5	5	6
c-C_4F_8	0	0	0	13	13	7
HFC-23	15	25	23	18	22	22
SF_6	22	37	45	40	40	34
NF_3	3	3	11	26	40	30

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[20] 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 Partner reported emissions data received through the EPA's PFC Reduction/Climate Partnership and the EPA's PFC Emissions Vintage Model (PEVM), a model which estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001).[21] The availability and applicability of Partner data differs across the 1990 through 2007 time series. Consequently, emissions from semiconductor manufacturing were estimated using four distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, and 2007.

1990 through 1994

From 1990 through 1994, Partnership data was unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[22] 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet developed.

PEVM is based on the recognition that PFC 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 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),[23] and (2) product type (discrete, memory or logic).[24] 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. 2007).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions. The emission factor is used to estimate world uncontrolled emissions using publicly available data on world silicon consumption.

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

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[21] 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 report their PFC emissions to the EPA by way of a third party, which aggregates the emissions.

[22] 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.

[23] By decreasing features of IC 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 the smallest feature sizes (65 nm) 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).

[24] 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.

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 2007).

2000 through 2006

The emission estimate for the years 2000 through 2006—the period during which Partners began the consequential application of PFC-reduction measures—was estimated using a combination of Partner-reported emissions and 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 and the method described above. This is because non-Partners are assumed not to have implemented any PFC-reduction measures, and PEVM models emissions without such measures. 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.[25,26] Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see, ITRS, 2007 and Semiconductor Equipment and Materials Industry 2008).[27,28,29]

2007

For the year 2007, emissions were also estimated using a combination of Partner reported emissions and PEVM modeled emissions; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 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. Had the method used to estimate the 2000 through 2006 emissions (described above) been employed, the emissions estimated for 2007 would have been 1.5 percent higher

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[25] 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.

[26] Generally 5 percent or less of the fields needed to estimate TMLA shares are missing values in the World Fab Watch databases. In the 2007 World Fab Watch database used to generate the 2006 non-Partner TMLA capacity share, these missing values were replaced with the corresponding mean TMLA across fabs manufacturing similar classes of products. However, the impact of replacing missing values on the non-Partner TMLA capacity share was inconsequential.

[27] 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 WFW 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 percentage points. 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.

[28] 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 not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[29] 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.

because the estimate of uncontrolled non-Partner emissions would have been overstated by 2.5 percent.[30]

Second, the scope of the 2007 estimate is expanded relative to the estimates for the years 2000 through 2006 to include emissions from Research and Development fabs. This was feasible through the use of more detailed data published in the World Fab Forecast. PEVM databases are updated annually as described above. The published world average capacity utilization for 2007 was used for production fabs while for R&D fabs, a 20 percent figure was assumed. Inclusion of R&D fabs increased the estimated emissions by less than 1 percent.

Gas-Specific Emissions

Two different approaches were also used to estimate the distribution of emissions of specific fluorinated gases. Before 1999, when 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. This distribution was based upon the average fluorinated-gas purchases by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001). For the 2000 through 2007 period, the 1990 through 1999 distribution was assumed to apply to the non-Partners. Partners, however, began reporting gas-specific emissions during this period. Thus, gas-specific emissions for 2000 through 2007 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.

Data Sources

Partners estimate their emissions using a range of methods. For 2007, it is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *IPCC Guidelines for National Greenhouse Inventories* (2006). The Partners with relatively high emissions use leading-edge manufacturing technology, the newest process equipment. When purchased, this equipment is supplied with fluorinated-gas emission factors, measured using industry standard guidelines (International Sematech 2006). The larger emitting Partners likely use these process-specific emission factors instead of the somewhat less representative default emission factors provided in the IPCC guidelines. Data used to develop emission estimates are attributed in part to estimates provided by the members of the Partnership, and in part from data obtained from PEVM estimates. Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the *Semiconductor Equipment and Materials Industry (SEMI) World Fab Forecast* (formerly *World Fab Watch*) database (1996 through 2008). Estimates of world average capacity utilizations for 2007 were obtained from *Semiconductor International Capacity Statistics* (SICAS). Estimates of silicon consumed by linewidth from 1990 through 2007 were derived from information from VLSI Research (2008), and the number of layers per linewidth was obtained from International Technology Roadmap for Semiconductors: 2006 Update (Burton and Beizaie 2001, ITRS 2007, ITRS 2008).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

$$\text{U.S. emissions} = \sum \text{Partnership gas-specific submittals} + [(\text{non-Partner share of world TMLA}) \times (\text{PEVM emission factor} \times \text{world TMLA})]$$

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the four quantities on the right side of the equation. Estimates of uncertainty for the four quantities were in turn developed using the estimated uncertainties associated with the individual inputs to each quantity, error propagation analysis, Monte Carlo simulation and expert judgment. The relative uncertainty associated with World TMLA estimate in 2007 is ±9 percent, based on the uncertainty estimate obtained from discussions with VLSI, Inc. For the share of World layer-weighted silicon capacity accounted for by non-Partners, a relative uncertainty of ±8 percent was estimated based

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[30] 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.

on a separate Monte Carlo simulation to account for the random occurrence of missing data in the *World Fab Watch* database. For the aggregate PFC emissions data supplied to the partnership, a relative uncertainty of ±50 percent was estimated for each gas-specific PFC emissions value reported by an individual Partner, and error propagation techniques were used to estimate uncertainty for total Partnership gas-specific submittals.[31] A relative error of approximately 10 percent was estimated for the PEVM emission factor, based on the standard deviation of the 1996 to 1999 emission factors.[32] All estimates of uncertainties are given at 95-percent confidence intervals.

In developing estimates of uncertainty, consideration was also given to the nature and magnitude of the potential bias that World activity data (i.e., World TMLA) might have in its estimates of the number of layers associated with devices manufactured at each technology node. The result of a brief analysis indicated that U.S. TMLA overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. The same upward bias is assumed for World TMLA, and is represented in the uncertainty analysis by deducting the absolute bias value from the World activity estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-92. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 4.7 and 5.7 Tg CO_2 Eq. at a 95 percent confidence level. This range represents 9 percent below to 9 percent above the 2007 emission estimate of 5.2 Tg CO_2 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.

Planned Improvements

With the exception of possible future updates to emission factors, the method to estimate non-Partner related emissions (i.e., PEVM) is not expected to change. Future improvements to the national emission estimates will primarily be associated with determining the portion of national emissions to attribute to Partner report totals (about 80 percent in recent years) and improvements in estimates of non-Partner totals. As the nature of the Partner reports change through time and industry-wide reduction efforts increase, consideration will be given to what emission reduction efforts—if any—are likely to be occurring at non-Partner facilities. Currently, none are assumed to occur.

Another point of consideration for future national emissions estimates is the inclusion of PFC emissions from heat transfer fluid (HTF) loss to the atmosphere and the production of photovoltaic cells (PVs). Heat transfer fluids, of which some are liquid perfluorinated compounds, are used during testing of semiconductor devices and, increasingly, are used to manage heat during the manufacture of semiconductor devices. Evaporation of these fluids is a source of emissions (EPA 2006). PFCs are also used during manufacture of PV cells that use silicon technology, specifically, crystalline, polycrystalline and amorphous silicon technologies. PV

Table 4-92: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)[a]	Uncertainty Range Relative to Emission Estimate[b] (Tg CO_2 Eq.)		(%)	
			Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, and SF_6	5.2	4.7	5.7	-9%	+9%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-90.
[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[c] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

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[31] Error propagation resulted in Partnership gas-specific uncertainties ranging from 18 to 36 percent.

[32] The average of 1996 to 1999 emission factor is used to derive the PEVM emission factor.

manufacture is growing in the United States, and therefore may be expected to constitute a growing share of U.S. PFC emissions from the electronics sector.

4.22. Electrical Transmission and Distribution (IPCC Source Category 2F7)

The largest use of SF_6, both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF_6 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 12.7 Tg CO_2 Eq. (0.5 Gg) in 2007. This quantity represents a 53 percent decrease from the estimate for 1990 (see Table 4-93 and Table 4-94). This decrease is believed to have two causes: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.

Table 4-93: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Tg CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	26.5	0.3	26.8
1995	21.0	0.5	21.6
2000	14.4	0.7	15.1
2005	13.2	0.8	14.0
2006	12.4	0.8	13.2
2007	12.0	0.7	12.7

Table 4-94: SF_6 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Gg)

Year	Emissions
1990	1.1
1995	0.9
2000	0.6
2005	0.6
2006	0.6
2007	0.5

Methodology

The estimates of emissions from electric 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.

1999 through 2007 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2007 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (partners), which began in 1999, and (2) the relationship between emissions and utilities' transmission miles as reported in the 2001, 2004 and 2007 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2007, partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 42 percent and 47 percent of total U.S. transmission miles. For each year, the emissions reported by or estimated for partner utilities were added to the emissions estimated for utilities that have never participated in the Partnership (i.e., non-partners).[33]

Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on partner-specific transmission mile growth rates. In 2007, non-reporting partners accounted for approximately 8 percent of the total emissions attributed to partner utilities.

Emissions from non-partners in every year since 1999 were estimated using the results of a regression analysis that showed that the emissions from reporting utilities were most strongly correlated with their transmission miles. The results of this analysis are not surprising given that, in the United States, SF_6 is contained primarily in transmission equipment rated at or above 34.5 kV. The equations were developed based on the 1999 SF_6 emissions reported by 43 partner utilities (representing approximately 24 percent of U.S. transmission miles), and 2000 transmission mileage data obtained from the 2001 UDI Directory of Electric Power Producers and Distributors (UDI 2001). Two equations were developed, one for small and one for large utilities (i.e., with fewer or more 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 small and large transmission networks. The same equations were used to estimate non-partner emissions in 1999 and every year thereafter because non-partners were assumed not to have implemented any changes that would have resulted in reduced emissions since 1999.

The regression equations are:

Non-Partner small utilities (less than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.89 \times \text{Transmission Miles}$$

Non-Partner large utilities (more than 10,000 transmission miles, in kilograms):

$$\text{Emissions (kg)} = 0.58 \times \text{Transmission Miles}$$

Data on transmission miles for each non-partner utility for the years 2000, 2003, and 2006 were obtained from the 2001, 2004, and 2007 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007). The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 and by over 55,000 miles between 2003 and 2006. These periodic increases are assumed to have occurred gradually, therefore transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and 2.8 percent between 2003 and 2006. Transmission miles in 2007 were then extrapolated from 2006 based on the 2.8 percent growth rate.

As a final step, total emissions were determined for each year by summing the partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), and the non-partner emissions (determined using the 1999 regression equations).

1990 through 1998 Emissions from Electric Power Systems

Because most participating utilities reported emissions only for 1999 through 2007, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global[34] emissions from this source during the 1990 to 1999 period. To estimate global emissions, the RAND survey of global SF_6 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 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). (Although equation 7.3 of the IPCC Guidelines appears in the discussion of substitutes for ozone depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

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[33] Partners in EPA's SF_6 Emission Reduction Partnership reduced their emissions by approximately 54% from 1999 to 2007.

[34] Ideally, sales to utilities in the U.S. between 1990 and 1999 would be used as a model. However, this information was not available. There are only two U.S. manufacturers of SF_6, so sensitive sales information is not concealed by aggregation.

Emissions (kilograms SF_6) = SF_6 purchased to refill existing equipment (kilograms) + SF_6 nameplate capacity[35] of retiring equipment (kilograms)

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 15.1 Tg CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. 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 discussion below).

1990 through 2007 Emissions from Manufacture of Electrical Equipment

The 1990 to 2007 emission estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 provided with new equipment. The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000; the quantities of SF_6 provided with new equipment for 2001 to 2007 were estimated using partner-reported data and the total industry SF_6 nameplate capacity estimate (131.8 Tg CO_2 Eq. in 2007). 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 2007 was calculated. This ratio was then multiplied by the total industry nameplate capacity estimate to derive the amount of SF_6 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

To estimate the uncertainty associated with emissions of SF_6 from electric transmission and distribution, uncertainties associated with three quantities were estimated: (1) emissions

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[35] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

from partners; (2) emissions from non-partners; and (3) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting and non-reporting partners. For reporting partners, individual partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all partner reported data was estimated to be 3.6 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting partners was assumed to be 20 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2007 from non-partners: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for non-partners. In addition, there is uncertainty associated with the assumption that the emission factor used for non-partner utilities (which accounted for approximately 58 percent of U.S. transmission miles in 2007) will remain at levels defined by partners who reported in 1999. However, the last source of uncertainty was not modeled.

Uncertainties were also estimated regarding the quantity of SF_6 supplied with equipment by equipment manufacturers, which is projected from partner provided nameplate capacity data and industry SF_6 nameplate capacity estimates, and the manufacturers' SF_6 emissions rate.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-95. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 10.0 and 15.5 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 22 percent above the emission estimate of 12.7 Tg CO_2 Eq.

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998, and emissions based on atmospheric measurements declined by 27 percent over the same period.

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from Dilo, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported 1990 through 1999 emissions to EPA showed a downward trend beginning in the mid-1990s.

Recalculations Discussion

Sulfur hexafluoride emission estimates for the period 1990 through 2006 were updated based on (1) new data from EPA's SF_6 Emission Reduction Partnership; (2) revisions to interpolated and extrapolated non-reported partner data; and (3) a revised regression equation coefficient for non-partner small utilities (fewer than 10,000 transmission miles). The new regression coefficient resulted from a revised 1999 emission estimate from a Partner of EPA's SF_6 Emission Reduction Partnership. This new emission estimate changed the regression coefficient from 0.88 to 0.89. Based on the revisions listed above, SF_6 emissions from electric transmission and distribution increased 1 percent or less for each year from 1990 through 2006.

Table 4-95: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	12.7	10.0	15.5	-21%	+22%

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

Box 4-1: Potential Emission Estimates of HFCs, PFCs, and SF_6

Emissions of HFCs, PFCs and SF_6 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- ***Byproduct emissions.*** Some emissions do not result from the consumption or use of a chemical, but are the unintended byproducts of another process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.
- ***Potential emissions that equal actual emissions.*** For some sources, such as magnesium production and processing, no delay between consumption and emission is assumed and, consequently, no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.

Table 4-96 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, and SF_6 from semiconductor manufacture, and SF_6 from magnesium production and processing and electrical transmission and distribution.[36] Potential emissions associated with the substitution for ozone depleting substances were calculated using the EPA's Vintaging Model. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the IPCC *Good Practice Guidance* (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the IPCC *Good Practice Guidance*. Potential SF_6 emissions estimates for electrical transmission and distribution were developed using U.S. utility purchases of SF_6 for electrical equipment. From 1999 through 2007, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems. U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 4-96: 2007 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (Tg CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	185.5	108.3
Aluminum Production	–	3.8
HCFC-22 Production	–	17.0
Semiconductor Manufacture	7.6	4.7
Magnesium Production and Processing	3.0	3.0
Electrical Transmission and Distribution	20.9	12.7

– Not applicable.

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[36] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

4.23. Industrial Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 2007 are reported in Table 4-97.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. 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 categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

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

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.

Table 4-97: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
NO_x	**591**	**607**	**626**	**534**	**527**	**520**
Other Industrial Processes	343	362	435	389	382	375
Chemical & Allied Product Manufacturing	152	143	95	64	64	64
Metals Processing	88	89	81	63	63	63
Storage and Transport	3	5	14	17	17	17
Miscellaneous[a]	5	8	2	2	2	2
CO	**4,125**	**3,959**	**2,216**	**1,744**	**1,743**	**1,743**
Metals Processing	2,395	2,159	1,175	895	895	894
Other Industrial Processes	487	566	537	445	444	444
Chemical & Allied Product Manufacturing	1,073	1,110	327	258	258	258
Storage and Transport	69	23	153	107	107	107
Miscellaneous[a]	101	102	23	39	40	40
NMVOCs	**2,422**	**2,642**	**1,773**	**2035**	**1950**	**1878**
Storage and Transport	1,352	1,499	1,067	1346	1280	1228
Other Industrial Processes	364	408	412	401	388	376
Chemical & Allied Product Manufacturing	575	599	230	226	221	216
Metals Processing	111	113	61	42	42	42
Miscellaneous[a]	20	23	3	20	19	17

[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.

Note: Totals may not sum due to independent rounding.

5. Solvent and Other Product Use

Greenhouse gas emissions are produced as a by-product of various solvent and other product uses. In the United States, emissions from Nitrous Oxide (N_2O) Product Usage, the only source of greenhouse gas emissions from this sector, accounted for less than 0.1 percent of total U.S. anthropogenic greenhouse gas emissions on a carbon equivalent basis in 2007 (see Table 5-1). Indirect greenhouse gas emissions also result from solvent and other product use, and are presented in Table 5-5 in gigagrams (Gg).

Table 5-1: N_2O Emissions from Solvent and Other Product Use (Tg CO_2 Eq. and Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
N_2O from Product Uses						
Tg CO_2 Eq.	4.4	4.6	4.9	4.4	4.4	4.4
Gg	14	15	16	14	14	14

5.1. Nitrous Oxide from Product Uses (IPCC Source Category 3D)

N_2O is a clear, colorless, oxidizing liquefied gas, with a slightly sweet odor. Two companies operate a total of five N_2O production facilities in the United States (Airgas 2007; FTC 2001). N_2O is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. As such, it is used to treat short-term pain, for sedation in minor elective surgeries, and as an induction anesthetic. 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 2007 was approximately 15 Gg (Table 5-2). N_2O emissions were 4.4 Tg CO_2 Eq. (14 Gg) in 2007 (Table 5-3). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 5-2: N_2O Production (Gg)

Year	Gg
1990	16
1995	17
2000	17
2005	15
2006	15
2007	15

Table 5-3: N_2O Emissions from N_2O Product Usage (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	4.4	14
1995	4.6	15
2000	4.9	16
2005	4.4	14
2006	4.4	14
2007	4.4	14

Methodology

Emissions from N_2O product usage were calculated by first multiplying the total amount of N_2O produced in the United States by the share of the total quantity of N_2O attributed to each end use. This value was then multiplied by the associated emission rate for each end use. After the emissions were calculated for each end use, they were added together to obtain a total estimate of N_2O product usage emissions. Emissions were determined using the following equation:

$$\text{N}_2\text{O Product Usage Emissions} = \\ \Sigma_i\ [\text{Total U.S. Production of N}_2\text{O}] \times \\ [\text{Share of Total Quantity of N}_2\text{O Usage by Sector i}] \times \\ [\text{Emissions Rate for Sector i}],$$

where,

i = sector.

The share of total quantity of N_2O usage by end use represents the share of national N_2O produced that is used by the specific subcategory (i.e., anesthesia, food processing, etc.). In 2007, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other categories combined used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide has declined significantly during the decade of the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). The N_2O 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 N_2O 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 N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed/reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* report (Heydorn 1997). N_2O 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 N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2003) provided a narrower range (i.e., 15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn

Table 5-4: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions From N_2O Product Usage ($Tg CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O Product Usage	N_2O	4.4	4.3	4.5	-2%	+2%

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

(1997). Tupman (2003) data are considered more industry-specific and current. Therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2003). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to unavailable data, production for 2004, 2005, 2006, and 2007 were held at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's Nitrous Oxide, North America report (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to unavailable data, the share of total quantity of N_2O usage data for 2004, 2005, 2006, and 2007 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 N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the 2006 IPCC Guidelines.

Uncertainty

The overall uncertainty associated with the 2007 N_2O emission estimate from N_2O product usage was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of production data, total market share of each end use, and the emission factors applied to each end use, respectively.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 5-4. N_2O emissions from N_2O product usage were estimated to be between 4.3 and 4.5 $Tg CO_2$ Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 2 percent below to 2 percent above the 2007 emissions estimate of 4.4 $Tg CO_2$ Eq.

Planned Improvements

Planned improvements include a continued evaluation of alternative production statistics for cross verification and a reassessment of subcategory usage to accurately represent the latest trends in the product usage, and 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 N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

5.2. Indirect Greenhouse Gas Emissions from Solvent Use

The use of solvents and other chemical products can result in emissions of various ozone precursors (i.e., indirect greenhouse gases).[1] Non-methane volatile organic compounds (NMVOCs), commonly referred to as "hydrocarbons," are the primary gases emitted from

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[1] Solvent 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 the Industrial Processes chapter.

most processes employing organic or petroleum based solvents. As some 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. In the United States, emissions from solvents are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The evaporation process varies depending on different solvent uses and solvent types. The major categories of solvent uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (i.e., electronics, etc.), dry cleaning, and non-industrial uses (i.e., uses of paint thinner, etc.).

Total emissions of NO_x, NMVOCs, and CO from 1990 to 2007 are reported in Table 5-5.

Table 5-5: Emissions of NO_x, CO, and NMVOC from Solvent Use (Gg)

Activity	1990	1995	2000	2005	2006	2007
NO_x	**1**	**3**	**3**	**5**	**5**	**5**
Surface Coating	1	2	3	5	5	5
Graphic Arts	+	1	+	+	+	+
Degreasing	+	+	+	+	+	+
Dry Cleaning	+	+	+	+	+	+
Other Industrial Processes[a]	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+
Other	NA	+	+	+	+	+
CO	**5**	**5**	**45**	**2**	**2**	**2**
Surface Coating	+	1	45	2	2	2
Other Industrial Processes[a]	4	3	+	+	+	+
Dry Cleaning	+	1	+	+	+	+
Degreasing	+	+	+	+	+	+
Graphic Arts	+	+	+	+	+	+
Non-Industrial Processes[b]	+	+	+	+	+	+
Other	NA	NA	+	+	+	+
NMVOCs	**5,216**	**5,609**	**4,384**	**3,881**	**3,867**	**3,855**
Surface Coating	2,289	2,432	1,766	1,590	1,584	1,579
Non-Industrial Processes[b]	1,724	1,858	1,676	1,457	1,452	1,447
Degreasing	675	716	316	283	282	281
Dry Cleaning	195	209	265	232	231	230
Graphic Arts	249	307	222	195	194	194
Other Industrial Processes[a]	85	87	98	88	88	88
Other	+	+	40	36	36	36

+ Does not exceed 0.5 Gg.

[a] Includes rubber and plastics manufacturing, and other miscellaneous applications.

[b] Includes cutback asphalt, pesticide application adhesives, consumer solvents, and other miscellaneous applications.

Note: Totals may not sum due to independent rounding.

Methodology

Emissions were calculated by aggregating solvent use data based on information relating to solvent 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 solvent-specific emission factors to the amount of solvents used for surface coatings, an estimate of emissions was obtained. Emissions of CO and NO_x result primarily from thermal and catalytic incineration of solvent-laden gas streams from painting booths, printing operations, and oven exhaust.

These emission estimates were obtained from preliminary data (EPA 2009), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of solvent purchased) 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

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and the reliability of correlations between activity data and actual emissions.

6. 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 6-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as 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.

In 2007, the Agricultural sector was responsible for emissions of 413.1 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 6 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 about 24 percent and 8 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

Figure 6-1

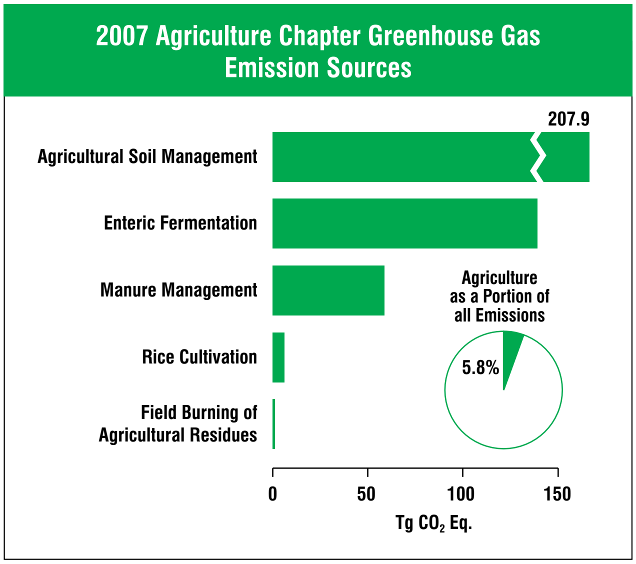
2007 Agriculture Chapter Greenhouse Gas Emission Sources

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**171.4**	**186.3**	**180.5**	**185.5**	**186.8**	**190.0**
Enteric Fermentation	133.2	143.6	134.4	136.0	138.2	139.0
Manure Management	30.4	34.5	37.9	41.8	41.9	44.0
Rice Cultivation	7.1	7.6	7.5	6.8	5.9	6.2
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.9	0.8	0.9
N_2O	**212.8**	**215.6**	**218.9**	**225.5**	**223.5**	**223.1**
Agricultural Soil Management	200.3	202.3	204.5	210.6	208.4	207.9
Manure Management	12.1	12.9	14.0	14.2	14.6	14.7
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.5	0.5
Total	**384.2**	**402.0**	**399.4**	**410.8**	**410.3**	**413.1**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**8,161**	**8,873**	**8,597**	**8,833**	**8,894**	**9,047**
Enteric Fermentation	6,342	6,837	6,398	6,474	6,580	6,618
Manure Management	1,447	1,642	1,804	1,991	1,993	2,093
Rice Cultivation	339	363	357	326	282	293
Field Burning of Agricultural Residues	33	32	38	41	39	42
N_2O	**686**	**696**	**706**	**727**	**721**	**720**
Agricultural Soil Management	646	653	660	679	672	671
Manure Management	39	42	45	46	47	47
Field Burning of Agricultural Residues	1	1	1	2	2	2

Note: Totals may not sum due to independent rounding.

soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 67 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2007, CH_4 emissions from agricultural activities increased by 11 percent, while N_2O emissions fluctuated from year to year, but overall increased by 5 percent.

6.1. Enteric Fermentation (IPCC Source Category 4A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, 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 6-3 and Table 6-4. Total livestock CH_4 emissions in 2007 were 139.0 Tg CO_2 Eq. (6,618 Gg). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2007. Emissions from dairy cattle in 2007 accounted for 23 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2007, emissions from enteric fermentation have increased by 4.3 percent. Generally, emissions decreased from 1995 to 2004, though with slight increases in 2002 and 2003. This trend was mainly due to decreasing populations of both beef and dairy cattle and increased digestibility of feed for feedlot cattle. Emissions have increased from 2004 through 2007, as both dairy and beef populations have undergone increases. During the timeframe of this analysis, populations of sheep have

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2006	2007
Beef Cattle	94.6	106.7	98.8	98.4	100.0	100.2
Dairy Cattle	32.8	31.3	30.2	30.8	31.4	31.9
Horses	1.9	1.9	2.0	3.5	3.5	3.5
Sheep	1.9	1.5	1.2	1.0	1.0	1.0
Swine	1.7	1.9	1.9	1.9	1.9	2.0
Goats	0.3	0.2	0.3	0.3	0.3	0.3
Total	**133.2**	**143.6**	**134.4**	**136.0**	**138.2**	**139.0**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	2000	2005	2006	2007
Beef Cattle	4,504	5,082	4,707	4,687	4,762	4,772
Dairy Cattle	1,563	1,490	1,440	1,468	1,497	1,521
Horses	91	92	94	166	166	166
Sheep	91	72	56	49	50	49
Swine	81	88	88	92	93	98
Goats	13	12	12	13	13	13
Total	**6,342**	**6,837**	**6,398**	**6,474**	**6,580**	**6,618**

Note: Totals may not sum due to independent rounding.

decreased 46 percent since 1990 while horse populations have increased over 80 percent, mostly since 1999. Goat and swine populations have increased 1 percent and 21 percent, respectively, during this timeframe.

Methodology

Livestock 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 CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle except for bulls. Emission estimates for other domesticated animals (horses, sheep, swine, goats, and bulls) 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 EPA and used to estimate cattle CH_4 emissions from enteric fermentation, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

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 Steers)
  - 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 3.9. 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 Quick Stats database (USDA 2008).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each population category. The IPCC recommends Y_m values 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, rather than using the recommended IPCC values. 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, expert opinion, and modeling of animal physiology. The diet characteristics for dairy cattle were from Donovan (1999), while those for beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). Values from EPA (1993) were used for dairy replacement heifers. For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight and weight gains for cattle were estimated from Enns (2008), Patton et al. (2008), Lippke et al. (2000), Pinchack et al., (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets and weights in the United States.

To estimate CH_4 emissions from all cattle types except bulls and calves younger than 7 months,[1] the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis, to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, and heifer feedlot animals. To estimate emissions from cattle, population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.9.

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 CH_4 emissions from livestock in the United States from 1990 through 2007. Also, 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 these other livestock types, except horses and goats, as well as feedlot placement information were obtained for all years from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 2008). Horse population data were obtained from the FAOSTAT database (FAO 2008), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained for 1992, 1997, and 2002 (USDA 2008); these data were interpolated and extrapolated to derive estimates for the other years. Methane emissions

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[1] Emissions from bulls are estimated using a Tier 1 approach because it is assumed there is minimal variation in population and diets; because calves younger than 7 months consume mainly milk and the IPCC recommends the use of methane conversion factor of zero for all juveniles consuming only milk, this results in no methane emissions from this subcategory of cattle.

from sheep, goats, swine, and horses 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. The methodology is the same as that recommended by IPCC (2006).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty

Quantitative uncertainty analysis for this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory report. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2007 activity data and emission factor input variables used in the current submission. Consequently, these uncertainty estimates were directly applied to the 2007 emission estimates.

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 capture the fact that these variables cannot be negative. 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 our 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 (Table 6-5) indicate that, on average, the emission estimate range of this source is approximately 123.7 to 164.0 Tg CO_2 Eq., calculated as 11 percent below and 18 percent above the actual 2007 emission estimate of 139.0 Tg CO_2 Eq. Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions as well as the largest degree of uncertainty in the inventory emission estimates. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates because there is a higher degree of uncertainty among the FAO population estimates used for horses than for the USDA population estimates used for swine, goats, and sheep.

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

Table 6-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	139.0	123.7	164.0	-11%	+18%

[a] Range of emission 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 submitted in 2003 and applied to the 2007 estimates.

emission estimates. As described below, particular emphasis this year was placed on revising CEFM weight assumptions and modifications of the stocker population estimates in the transition matrix, which required further QA/QC to ensure consistency of estimates generated by the updated model.

Recalculations Discussion

There were several modifications to the estimates relative to the previous Inventory that had an effect on emission estimates, including the following:

- During the QA/QC process, it was noted that a portion of the steer and heifer populations that were held aside (e.g., not eligible to be placed in feedlots) to establish the stocker population for the following January were inadvertently left out of the emissions calculations. These heifer and steer stocker populations are now included.
- An additional adjustment was made to the CEFM to allow feedlot placements for the 700–800 lbs category to use excess animals from the over 800 lbs category if insufficient animals are available to place in a given month at 700–800 lbs. This process reduced the discrepancy in the model between actual placement numbers by weight category from USDA and available animals within the transition matrix.
- Calf weight at 7 months was adjusted to be equal for all months, as current research indicated that evidence was not sufficient to suggest that calf weight at weaning differs by birth month.
- Mature weight for beef cows was revised based on annual data collected from 1989 through 2007, as was replacement weight at 15 and 24 months.
- Mature weight for dairy cows was adjusted to 1,550 for all years, and replacement weight at 15 and 24 months was adjusted accordingly.
- Monthly weight gain for stockers was increased to 1.83 lbs per day starting in 2000, and a linear function was used to determine adjustments from previous estimates between 1989 and 2000.
- Bulls were added to the CEFM calculations for the first time, as previously they had been calculated separately; however, the estimates are still carried out with the Tier 1 approach, so this change did not result in any changes in emissions from previous years.
- The USDA published revised population estimates that affected historical emissions estimated for swine in 2006. In addition, some historical population estimates for certain beef and dairy populations were also updated as a result of changes in USDA inputs.
- As a result of these changes, dairy cattle emissions increased an average of 65 Gg (4.6 percent) per year and beef cattle increased an average of 423 Gg (9.7 percent) per year over the entire time series relative to the previous Inventory. Historical emission estimates for swine in 2006 increased by less than one half of one percent as a result of the USDA revisions described above.

Planned Improvements

Continued research and regular updates are necessary to maintain a current model of cattle diet characterization, feedlot placement data, rates of weight gain and calving, among other data inputs. Research is currently underway to update the diet assumptions. There are a variety of models available to predict CH_4 production from cattle. Four of these models (two mechanistic, and two empirical) are being evaluated to determine appropriate Y_m and DE values for each cattle type and state. In addition to the model evaluation, separate research is being conducted to update the assumptions used for cattle diet components for each animal type. At the conclusion of both of these updates, it is anticipated that a peer-reviewed article will be published and will serve as the basis for future emission estimates for enteric fermentation.

In addition to the diet characteristics research discussed above several revisions will be investigated, including:

- Estimating bull emissions using the IPCC Tier 2 approach;
- Updating input variables that are from older data sources, such as beef births by month and beef cow lactation rates;
- Continue to evaluate and improve the CEFM handling of the differences between the USDA feedlot placement data by weight category and the number of animals that are available for placement by weight class according to the CEFM transition matrix;
- The possible breakout of other animal types (i.e., sheep, swine, goats, horses) from national estimates to state-level estimates; and

- Including bison in the estimates for other domesticated animals.

These updates may result in significant changes to some of the activity data used in generating emissions. Additionally, since these revised inputs will be state-specific and peer-reviewed, uncertainty ranges around these variables will likely decrease. As a consequence, the current uncertainty analysis will become outdated, and a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Direct N_2O emissions are produced as part of the N cycle through the nitrification and denitrification of the organic N in livestock manure and urine.[2] Indirect N_2O emissions are produced as result of the volatilization of N as ammonia (NH_3) and oxides of nitrogen (NO_x) and runoff and leaching of N during treatment, storage and transportation.

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 materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

The production of direct N_2O 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 N_2O emissions to occur, the manure must first be handled aerobically where NH_3 or organic N is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (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 N_2O in the waste management system (WMS). Indirect N_2O emissions are produced when N is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that results in exposure 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 does not include any leaching losses.

Estimates of CH_4 emissions in 2007 were 44.0 Tg CO_2 Eq. (2,093 Gg), 45 percent higher than in 1990. Emissions increased on average by 0.8 Tg CO_2 Eq. (2.5 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 51 and 60 percent, respectively. Although the majority of manure in the United States is handled as a solid, producing little CH_4, 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 limiting

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[2] Direct and indirect N_2O emissions from manure and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (e.g., lagoon, pit, etc.) and from livestock manure and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector.

the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. 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 facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, and 2002 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005). Methane emissions from horses have nearly doubled since 1990 (an 82 percent increase from 1990 to 2007); however, this is due to population increases rather than changes in manure management practices. Overall, horses contribute only 2 percent of CH_4 emissions from animal manure management. From 2006 to 2007, there was a 5 percent increase in total CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

In 2007, total N_2O emissions were estimated to be 14.7 Tg CO_2 Eq. (47 Gg); in 1990, emissions were 12.1 Tg CO_2 Eq. (39 Gg). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have remained fairly steady since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 22 percent increase from 1990 to 2007 and a 1 percent increase from 2006 through 2007.

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal catagory.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	1995	2000	2005	2006	2007
CH_4[a]	**30.4**	**34.5**	**37.9**	**41.8**	**41.9**	**44.0**
Dairy Cattle	11.3	12.5	14.7	17.2	17.5	18.1
Beef Cattle	2.6	2.6	2.5	2.4	2.5	2.4
Swine	13.1	16.0	17.5	18.6	18.3	19.7
Sheep	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+
Poultry	2.8	2.7	2.6	2.7	2.7	2.7
Horses	0.5	0.4	0.5	0.8	0.8	0.8
N_2O[b]	**12.1**	**12.9**	**14.0**	**14.2**	**14.6**	**14.7**
Dairy Cattle	3.5	3.5	3.6	3.7	3.8	3.9
Beef Cattle	5.5	6.0	6.7	6.5	6.7	6.7
Swine	1.2	1.4	1.4	1.5	1.5	1.6
Sheep	0.1	0.2	0.3	0.3	0.4	0.3
Goats	+	+	+	+	+	+
Poultry	1.5	1.6	1.7	1.7	1.8	1.8
Horses	0.2	0.2	0.2	0.4	0.4	0.4
Total	**42.5**	**47.4**	**51.9**	**56.0**	**56.4**	**58.7**

+ Less than 0.05 Tg CO_2 Eq.

[a] Includes CH_4 emission reductions due to CH_4 collection and combustion by anaerobic digestion utilization systems.

[b] Includes both direct and indirect N_2O emissions.

Note: Totals may not sum due to independent rounding.

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	1995	2000	2005	2006	2007
CH_4[a]	**1,447**	**1,642**	**1,804**	**1,991**	**1,993**	**2,093**
Dairy Cattle	538	597	701	820	833	863
Beef Cattle	124	125	118	114	119	116
Swine	624	764	832	887	870	940
Sheep	7	5	4	4	4	4
Goats	1	1	1	1	1	1
Poultry	131	128	126	127	128	130
Horses	22	21	22	39	39	39
N_2O[b]	**39**	**42**	**45**	**46**	**47**	**47**
Dairy Cattle	11	11	12	12	12	13
Beef Cattle	18	19	22	21	22	22
Swine	4	5	5	5	5	5
Sheep	+	1	1	1	1	1
Goats	+	+	+	+	+	+
Poultry	5	5	5	6	6	6
Horses	1	1	1	1	1	1

+ Less than 0.5 Gg.

[a] Includes CH_4 emission reductions due to CH_4 collection and combustion by anaerobic digestion utilization systems.

[b] Includes both direct and indirect N_2O emissions.

Note: Totals may not sum due to independent rounding.

from manure management for this Inventory. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of CH_4 emissions:

- Animal population data (by animal type and state);
- Typical Animal Mass (TAM) data (by animal type);
- Portion of manure managed in each Waste Management System (WMS), by state and animal type;
- Volatile solids (VS) production rate (by animal type and state or U.S.);
- CH_4 producing potential (B_o) of the volatile solids (by animal type); and
- Methane Conversion Factors (MCF), representing the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection/utilization 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 2007 for all livestock types, except horses and goats were obtained from the USDA National Agricultural Statistics Service (NASS). Horse population data were obtained from the Food and Agriculture Organization (FAO) FAOSTAT database (FAO 2008). Goat population data for 1992, 1997, and 2002 were obtained from the *Census of Agriculture* (USDA 2005).
- The TAM is an annual average weight which was obtained for each animal type from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996a), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999) and others (EPA 1992, Shuyler 2000, and Safley 2000).
- WMS usage was estimated for swine and dairy cattle for different farm size categories using data from USDA (USDA 1996b, 1998, 2000a) and EPA (ERG 2000a, EPA 2002a, 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 2000b, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

- VS production rates for all cattle except for bulls and calves were calculated for each state and animal type in the CEFM, which is described in section 6.1, Enteric Fermentation. VS production rates for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996a) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1999).
- The maximum CH_4 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, and 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.
- Anaerobic digestion system data were obtained from the EPA AgSTAR Program, including information presented in the AgSTAR Digest (EPA 2000, 2003b, 2006).
- Emissions from anaerobic digestion systems were estimated based on the methodology described in EPA's Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Types Managing Manure with Biogas Recovery Systems (EPA 2008).

To estimate CH_4 emissions, first the annual amount of VS (kg per year) from manure that is excreted in each WMS for each animal type, state, and year was calculated. 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.

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) was multiplied by the maximum CH_4 producing capacity of the VS (B_o) (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4).

For anaerobic digestion systems, the maximum CH_4 producing capacity of the VS (B_o) (m^3 CH_4 per kg VS) was multiplied by an estimated CH_4 production value (percent), assumed values of the system collection efficiency (CE) (percent), an assumed value of the system destruction efficiency (DE) (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4) (ERG 2008). Anaerobic digestion systems were assumed to produce 90 percent of the maximum CH_4 producing capacity of the VS (B_o). The CH_4 CE of covered lagoon systems was estimated to be 75 percent, and the CH_4 CE of complete mix and plug flow anaerobic digestion systems was assumed to be 99 percent (EPA 2008). Any CH_4 that was not collected was assumed to be emitted as leakage. A DE from flaring or burning in an engine is estimated to be 98 percent; therefore, the amount of CH_4 that would not be flared or combusted and would be emitted is 2 percent (EPA 2008).

The CH_4 emissions for each WMS (including anaerobic digestion systems), state, and animal type were summed to determine the total U.S. Methane emissions from manure management.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect N_2O 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 (N_{ex});
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volitalization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of ammonia and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

N_2O 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:

- N excretion rates from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all animal types except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE1999) were used for these animal types.
- All N_2O emissions factors (direct and indirect) were from IPCC (IPCC 2006).
- 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 U.S. 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 3.1).

To estimate N_2O emissions, first the amount of $N_{excreted}$ (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the N excretion rate (N_{ex}, in kg N per 1000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of $N_{excreted}$ (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EFWMS, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal and WMS to determine the total direct N_2O emissions (kg of N_2O per year).

Then, indirect N_2O emissions from volatilization (kg N_2O 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 ($Frac_{gas}$) divided by 100, and the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Next, indirect N_2O emissions from runoff and leaching (kg N_2O per year) were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions.

The direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year).

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001 (EPA 2003a, ERG 2003) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. No significant changes occurred in the methods, data or other factors that influence the uncertainty ranges around the 2007 activity data. Consequently, these uncertainty estimates were directly applied to the 2007 emission estimates.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2007 were estimated to be between 36.0 and 52.8 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2007 emission estimate of 44.0 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 12.3 and 18.2 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2007 emission estimate of 14.7 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	44.0	36.0	52.8	-18%	+20%
Manure Management	N_2O	14.7	12.3	18.2	-16%	+24%

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

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 CH_4 and N_2O emissions from manure management. 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.

Recalculations Discussion

For the current Inventory, anaerobic digester systems were incorporated into the WMS distributions in the CH_4 estimates using the existing WMS distributions and EPA AgSTAR data. Emissions for anaerobic digestion systems were also calculated using an assumed CH_4 production rate, collection efficiency, and combustion efficiency (ERG 2008).

Using the APHIS 2001 Sheep report, the WMS distribution for sheep was updated. The APHIS report presents regional percentages of sheep and lambs that are primarily managed in open range/pasture, fenced range/pasture, farms, or feedlots in 2001 (USDA 2003). WMS data for sheep were previously obtained from USDA NASS sheep report for years 1990 through 1993 (USDA 1994). The WMS data for years 1994 through 2000 were calculated assuming a linear progression from 1993 to 2001. Due to lack of additional data, data for years 2002 and beyond were assumed to be the same as 2001.

The CEFM produces volatile solids data for cattle that are used in the manure management estimates. The CEFM team implemented methodological changes to the VS estimation, which created changes in VS data and changes in the amount of methane estimated for manure management (see Section 6.1, Enteric Fermentation).

With these recalculations, CH_4 emission estimates from manure management systems are slightly higher than reported in the previous Inventory for swine and slightly lower for dairy cattle. On average, annual CH_4 emission estimates are less than those of the previous Inventory by 1.7 percent.

Nitrous oxide emission estimates from manure management systems have increased for all years for beef cattle and since 1994 for sheep in the current Inventory as compared to the previous Inventory due to the recalculations. Overall the total emission estimates for the current Inventory increased by 1.2 percent, relative to the previous Inventory.

Planned Improvements

The manure management emission estimates will be updated to reflect changes in the Cattle Enteric Fermentation Model (CEFM). In addition, efforts will be made to ensure that the manure management emission estimates and CEFM are using the same data sources and variables where appropriate.

An updated version of the USDA *Agricultural Waste Management Field Handbook* became available in March 2008. This reference will be reviewed to determine if updates should be made to any of the inventory activity data.

The current inventory estimates take into account anaerobic digestion systems for only dairy and swine operations. Data from the AgSTAR Program will also be reviewed and anaerobic digestions systems that exist for other animal types will be incorporated.

The uncertainty analysis will be updated in the future to more accurately assess uncertainty of emission calculations. This update is necessary due to changes in emission calculation methodology in the current Inventory, including estimation of emissions at the WMS level and the use of new calculations and variables for indirect N_2O emissions.

6.3. Rice Cultivation (IPCC Source Category 4C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen present in the soil, causing anaerobic soil conditions. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root system) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead, so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with shallower flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). The factors that determine the amount of organic material available to decompose (i.e., organic fertilizer use, soil type, rice variety,[3] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season; the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in seven states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, and Texas.[4] Until 2006, rice was also cultivated in Oklahoma, but as of 2007 rice cultivation in the state ceased (Anderson 2008). Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers apply organic fertilizers in the form of

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[3] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

[4] A very small amount of rice is grown on about 20 acres in South Carolina; however, this amount was determined to be too insignificant to warrant inclusion in national emissions estimates.

residue from the previous rice crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of southwest Louisiana, Texas, and Florida often allow for a second, or ratoon, rice crop. Ratoon crops are much less common or non-existent in Arkansas, California, Mississippi, Missouri, Oklahoma, and northern areas of Louisiana. Methane emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow the stubble to decay aerobically), the amount of organic material that is available for anaerobic decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (and Table 6-10). In 2007, CH_4 emissions from rice cultivation were 6.2 Tg CO_2 Eq. (293 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2007, ranging from an annual decrease of 14 percent to an annual increase of 17 percent, there was an overall decrease of 14 percent over the seventeen-year period, due to an overall decrease in primary crop area.[5] The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Methodology

IPCC (2006) recommends using harvested rice areas, area-based daily emission factors (i.e., amount of CH_4 emitted per day per unit harvested area), and length of growing season to estimate annual CH_4 emissions from rice cultivation. This Inventory uses the recommended methodology and employs Tier 2 U.S.-specific emission factors derived from rice field measurements. State-specific and daily emission factors were not available, however, so average U.S. seasonal emission factors were used. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC (2006).

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	2000	2005	2006	2007
Primary	**5.1**	**5.6**	**5.5**	**6.0**	**5.1**	**4.9**
Arkansas	2.1	2.4	2.5	2.9	2.5	2.4
California	0.7	0.8	1.0	0.9	0.9	1.0
Florida	+	+	+	+	+	+
Louisiana	1.0	1.0	0.9	0.9	0.6	0.7
Mississippi	0.4	0.5	0.4	0.5	0.3	0.3
Missouri	0.1	0.2	0.3	0.4	0.4	0.3
Oklahoma	+	+	+	+	+	0.0
Texas	0.6	0.6	0.4	0.4	0.3	0.3
Ratoon	**2.1**	**2.1**	**2.0**	**0.8**	**0.9**	**1.2**
Arkansas	+	+	+	+	+	+
Florida	+	0.1	0.1	+	+	+
Louisiana	1.1	1.1	1.3	0.5	0.5	0.9
Texas	0.9	0.8	0.7	0.4	0.4	0.3
Total	**7.1**	**7.6**	**7.5**	**6.8**	**5.9**	**6.2**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

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[5] The 14 percent decrease occurred between 2005 and 2006; the 17 percent increase happened between 1993 and 1994.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	2000	2005	2006	2007
Primary	**241**	**265**	**260**	**287**	**241**	**234**
Arkansas	102	114	120	139	119	113
California	34	40	47	45	44	45
Florida	1	2	2	1	1	1
Louisiana	46	48	41	45	29	32
Mississippi	21	24	19	22	16	16
Missouri	7	10	14	18	18	15
Oklahoma	+	+	+	+	+	+
Texas	30	27	18	17	13	12
Ratoon	**98**	**98**	**97**	**39**	**41**	**59**
Arkansas	+	+	+	1	+	+
Florida	2	4	2	+	1	1
Louisiana	52	54	61	22	22	42
Texas	45	40	34	17	18	16
Total	**339**	**363**	**357**	**326**	**282**	**293**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11, and the area of ratoon crop area as a percent of primary crop area is shown in Table 6-12. Primary crop areas for 1990 through 2007 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987–1992* (USDA 1994), *Field Crops Final Estimates 1992–1997* (USDA 1998), *Field Crops Final Estimates 1997–2002* (USDA 2003), and *Crop Production Summary* (USDA 2005 through 2008). Source data for non-USDA sources of primary and ratoon harvest areas are shown in Table 6-13. California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990 through 2007 (Guethle 1999, 2000, 2001a, 2002 through 2008; Lee 2003 through 2007; Mutters 2002 through 2005; Street 1999 through 2003; Walker 2005, 2007, 2008).

To determine what CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments that involved atypical or nonrepresentative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[6] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged

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[6] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the aforementioned reasons. In addition, one measurement from the ratooned fields (i.e., the flux of 1,490 kg CH_4/hectare-season in Lindau and Bollich 1993) was excluded, because this emission rate is unusually high compared to other flux measurements in the United States, as well as IPCC (2006) default emission factors.

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	2000	2005	2006	2007
Arkansas						
Primary	485,633	542,291	570,619	661,675	566,572	536,220
Ratoon[a]	0	0	0	662	6	5
California	159,854	188,183	221,773	212,869	211,655	215,702
Florida						
Primary	4,978	9,713	7,801	4,565	4,575	4,199
Ratoon	2,489	4,856	3,193	0	1,295	840
Louisiana						
Primary	220,558	230,676	194,253	212,465	139,620	152,975
Ratoon	66,168	69,203	77,701	27,620	27,924	53,541
Mississippi	101,174	116,552	88,223	106,435	76,487	76,487
Missouri	32,376	45,326	68,393	86,605	86,605	72,036
Oklahoma	617	364	283	271	17	0
Texas						
Primary	142,857	128,693	86,605	81,344	60,704	58,681
Ratoon	57,143	51,477	43,302	21,963	23,675	21,125
Total Primary	**1,148,047**	**1,261,796**	**1,237,951**	**1,366,228**	**1,146,235**	**1,116,299**
Total Ratoon	**125,799**	**125,536**	**124,197**	**50,245**	**52,899**	**75,511**
Total	**1,273,847**	**1,387,333**	**1,362,148**	**1,416,473**	**1,199,135**	**1,191,810**

[a] Arkansas ratooning occurred only in 1998, 1999, 2005, and 2006 and was assumed to occur in 2007.
Note: Totals may not sum due to independent rounding.

Table 6-12: Ratooned Area as Percent of Primary Growth Area

State	1990	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Arkansas	0%		+	+	0%					+	+	+
Florida	50%			65%	41%	60%	54%	100%	77%	0%	28%	20%
Louisiana	30%				40%	30%	15%	35%	30%	13%	20%	35%
Texas	40%				50%	40%	37%	38%	35%	27%	39%	36%

+ Indicates ratooning rate less than 0.5 percent.

to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH$_4$/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH$_4$/hectare-season.

Uncertainty

The largest uncertainty in the calculation of CH$_4$ emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, in particular, fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 22 to 479 kg CH$_4$/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH$_4$/hectare-season. The uncertainty distributions around the primary and ratoon emission factors

Table 6-13: Non-USDA Data Sources for Rice Harvest Information

State/Crop	1990		1999	2000	2001	2002	2003	2004	2005	2006	2007
Arkansas											
Ratoon	Wilson (2002–2007)										
Florida											
Primary	Scheuneman (1999b, 1999c, 2000, 2001a)				Deren (2002)	Kirstein (2003, 2006)			Gonzales (2006–2008)		
Ratoon	Scheuneman (1999a)				Deren (2002)	Kirstein (2003–2004)		Cantens (2005)	Gonzales (2006–2008)		
Louisiana											
Ratoon	Bollich (2000)			Linscombe (1999, 2001a, 2002 through 2008)							
Oklahoma											
Primary	Lee (2003–2007)										Anderson (2008)
Texas											
Ratoon	Klosterboer (1999–2003)						Stansel (2004–2005)		Texas Ag Experiment Station (2006–2008)		

were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means was not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the Tier 2 Monte Carlo analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is ratooned, and the extent to which flooding outside of the normal rice season is practiced. Expert judgment was used to estimate the uncertainty associated with primary rice-cropped area for each state at 1 to 5 percent, and a normal distribution was assumed. Uncertainties were applied to ratooned area by state, based on the level of reporting performed by the state. No uncertainties were calculated for the practice of flooding outside of the normal rice season because CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-14. Rice cultivation CH_4 emissions in 2007 were estimated to be between 2.1 and 16.3 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 66 percent below to 164 percent above the actual 2007 emission estimate of 6.2 Tg CO_2 Eq.

Table 6-14: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	CH_4	6.2	2.1	16.3	-66%	+164%

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

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Planned Improvements

A possible future improvement is to create region-specific emission factors for rice cultivation. The current methodology uses a nationwide average emission factor, derived from several studies done in a number of states. The prospective improvement would take the same studies and average them by region, presumably resulting in more spatially-specific emission factors.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[7] A number of agricultural activities increase mineral nitrogen (N) availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add, or lead to greater release of, mineral N to the soil, 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 and cultivation of organic cropland soils (i.e., soils with a high organic matter content, otherwise known as histosols).[8] Other agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils and thereby affect direct emissions. Mineral N is also made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, which are influenced by agricultural management through impacts on moisture and temperature regimes in soils. These additional sources of mineral N are included at the recommendation of IPCC (2006) for complete accounting of management impacts on greenhouse gas emissions, as discussed in the Methodology section.[9] Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N,[10] and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water. Direct emissions from agricultural lands (i.e., croplands and grasslands) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. However, indirect N_2O emissions from all land-use types (cropland, grassland, forest lands, and settlements) are reported in this section.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2007 were 207.9 Tg CO_2 Eq. (671 Gg N_2O) (see Table 6-15 and Table 6-16). Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2007, although overall emissions were 3.8 percent higher in 2007 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. On

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[7] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of 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).

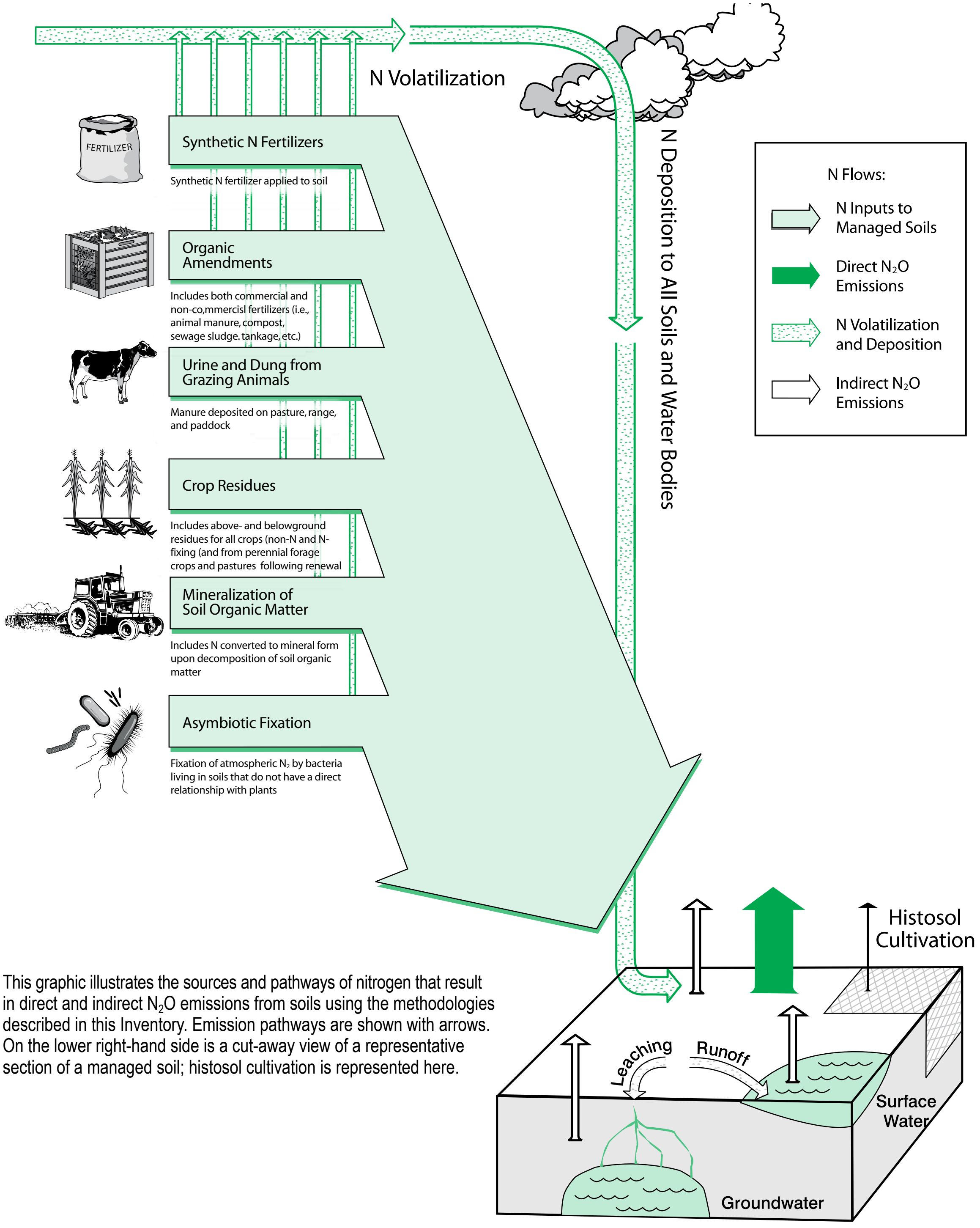
[8] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

[9] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[10] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate ammonium (NH_4^+), nitric acid (HNO_3), and NO_x.

Figure 6-2

Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

average, cropland accounted for approximately 69 percent of total direct emissions, while grassland accounted for approximately 31 percent. These percentages are about the same for indirect emissions since forest lands and settlements account for such a small percentage of total indirect emissions. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 6-17 and Table 6-18.

Table 6-15: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Direct	**158.9**	**165.8**	**169.2**	**174.4**	**170.7**	**172.0**
Cropland	106.3	114.2	119.4	122.2	119.9	121.9
Grassland	52.5	51.6	49.9	52.1	50.8	50.1
Indirect (All Land-Use Types)	**41.5**	**36.5**	**35.3**	**36.3**	**37.7**	**35.9**
Cropland	29.1	24.8	25.6	25.0	26.7	24.9
Grassland	12.0	11.2	9.1	10.5	10.3	10.3
Forest Land	+	+	0.1	0.1	0.1	0.1
Settlements	0.4	0.5	0.5	0.6	0.6	0.6
Total	**200.3**	**202.3**	**204.5**	**210.6**	**208.4**	**207.9**

+ Less than 0.05 Tg CO_2 Eq.

Table 6-16: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990	1995	2000	2005	2006	2007
Direct	**512**	**535**	**546**	**562**	**551**	**555**
Cropland	343	368	385	394	387	393
Grassland	169	167	161	168	164	162
Indirect (All Land-Use Types)	**134**	**118**	**114**	**117**	**122**	**116**
Cropland	94	80	82	81	86	80
Grassland	39	36	29	34	33	33
Forest Land	+	+	+	+	+	+
Settlements	1	2	2	2	2	2
Total	**646**	**653**	**660**	**679**	**672**	**671**

+ Less than 0.5 Gg N_2O

Table 6-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Cropland	**106.3**	**114.2**	**119.4**	**122.2**	**119.9**	**121.9**
Mineral Soils	**103.5**	**111.3**	**116.5**	**119.3**	**117.0**	**119.0**
Synthetic Fertilizer	41.0	46.6	45.4	48.3	46.5	47.3
Organic Amendments[a]	7.6	8.3	8.8	9.2	9.3	9.8
Residue N[b]	7.0	7.7	7.7	7.5	7.6	7.6
Mineralization and Asymbiotic Fixation	47.8	48.7	54.6	54.3	53.7	54.4
Organic Soils	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**52.5**	**51.6**	**49.9**	**52.1**	**50.8**	**50.1**
Synthetic Fertilizer	1.0	1.0	0.9	0.9	0.9	0.9
PRP Manure	10.3	10.9	10.2	10.7	10.5	10.4
Managed Manure[c]	1.0	0.9	0.9	1.0	1.0	1.0
Sewage Sludge	0.3	0.3	0.4	0.5	0.5	0.5
Residue N[d]	12.0	11.9	11.1	11.8	11.5	11.3
Mineralization and Asymbiotic Fixation	27.9	26.6	26.3	27.3	26.4	26.0
Total	**158.9**	**165.8**	**169.2**	**174.4**	**170.7**	**172.0**

[a] Organic amendment inputs include managed manure amendments, daily spread manure amendments, 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] Accounts for 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 6-18: Indirect N_2O Emissions from all Land-Use Types (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
Cropland	**29.1**	**24.8**	**25.6**	**25.0**	**26.7**	**24.9**
Volatilization & Atm. Deposition	7.8	8.9	9.0	9.2	10.1	8.9
Surface Leaching & Run-Off	21.3	15.9	16.6	15.8	16.6	16.0
Grassland	**12.0**	**11.2**	**9.1**	**10.5**	**10.3**	**10.3**
Volatilization & Atm. Deposition	5.6	5.6	5.0	5.2	5.2	5.3
Surface Leaching & Run-Off	6.4	5.6	4.0	5.3	5.1	5.0
Forest Land	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization & Atm. Deposition	+	+	+	+	+	+
Surface Leaching & Run-Off	+	+	0.1	0.1	0.1	0.1
Settlements	**0.4**	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**
Volatilization & Atm. Deposition	0.1	0.2	0.2	0.2	0.2	0.2
Surface Leaching & Run-Off	0.2	0.3	0.3	0.4	0.4	0.4
Total	**41.5**	**36.5**	**35.3**	**36.3**	**37.7**	**35.9**

+ Less than 0.05 Tg CO_2 Eq.

Figure 6-3 through Figure 6-6 show regional patterns in direct N_2O emissions, and also show N losses from volatilization, leaching, and runoff that lead to indirect N_2O emissions. Average annual emissions and N losses from croplands that produce major crops and from grasslands are shown for each state. Direct N_2O emissions from croplands tend to be high in the Corn Belt (Illinois, Iowa, Indiana, Ohio, southern Minnesota, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops. Direct emissions are also high in North Dakota, Kansas, and Texas, primarily from irrigated cropping and dryland wheat. Direct emissions are low in many parts of the eastern United States because a small portion of land is cultivated, and also low in many western states where rainfall and access to irrigation water are limited.

Direct emissions (Tg CO_2 Eq./state/year) from grasslands are highest in the central and western United States (Figure 6-4) where a high proportion of the land is used for cattle grazing. Some areas in the Great Lake states, the Northeast, and Southeast have moderate emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grazed land is much lower than states in the central and western United States.

Indirect emissions from croplands and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions, because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO_3^- leaching, N volatilization) do not respond in exactly the same manner as the processes that control direct emissions (nitrification and denitrification). For example, coarser-textured soils facilitate relatively high indirect emissions in Florida grasslands due to high rates of N volatilization and NO_3^- leaching, even though they have only moderate rates of direct N_2O emissions.

Figure 6-3

Major Crops, Average Annual Direct N_2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2007 (Tg CO_2 Eq./year)

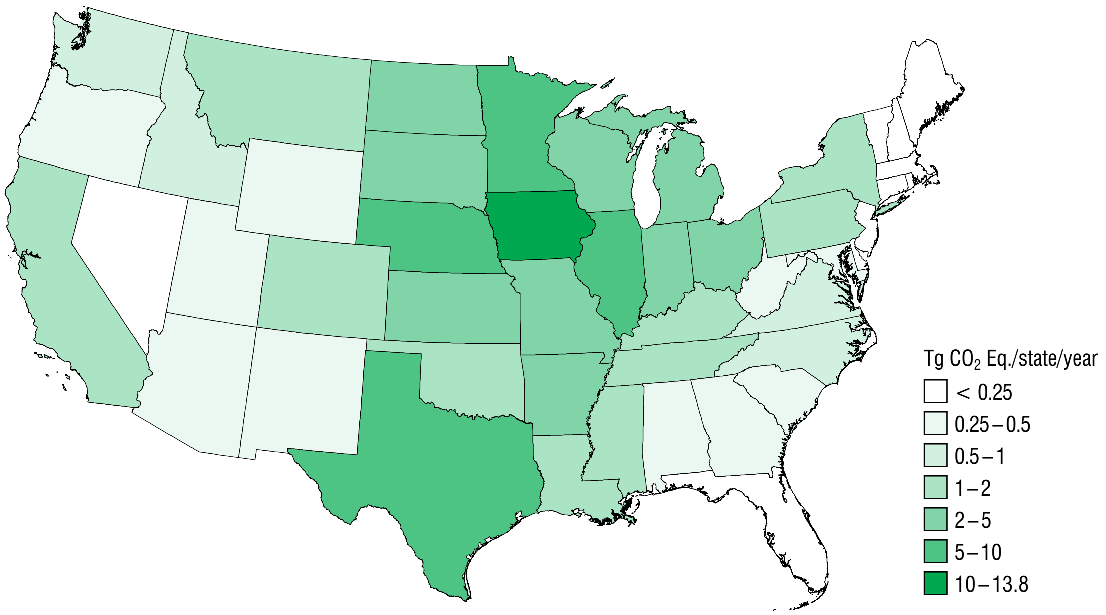


Figure 6-4

Grasslands, Average Annual Direct N_2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2007 (Tg CO_2 Eq./year)

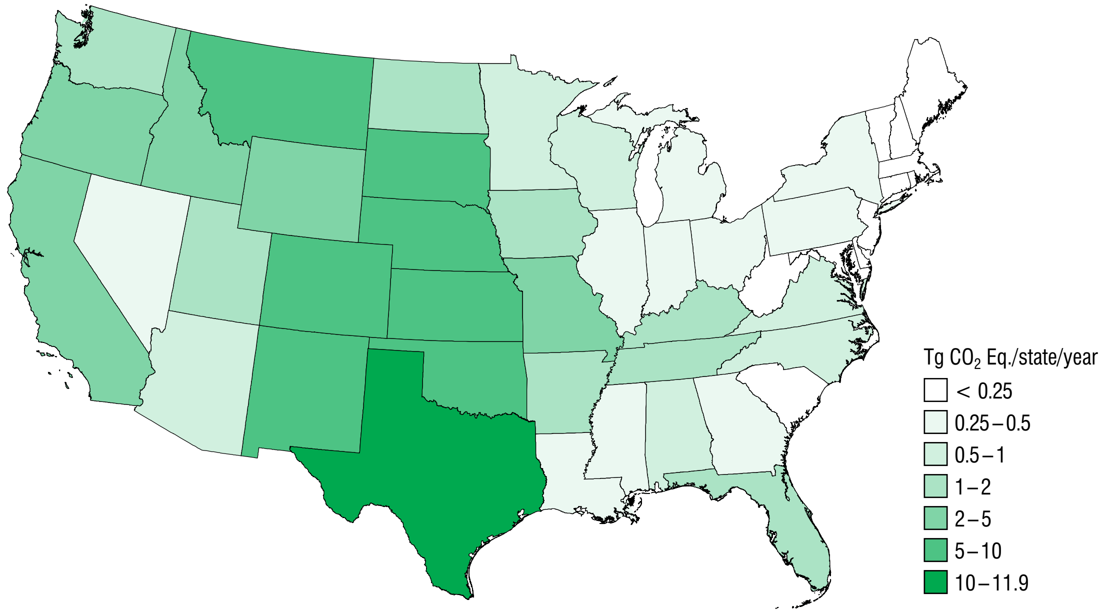


Figure 6-5

Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions by State, Estimated Using the DAYCENT Model, 1990–2007 (Gg N/year)

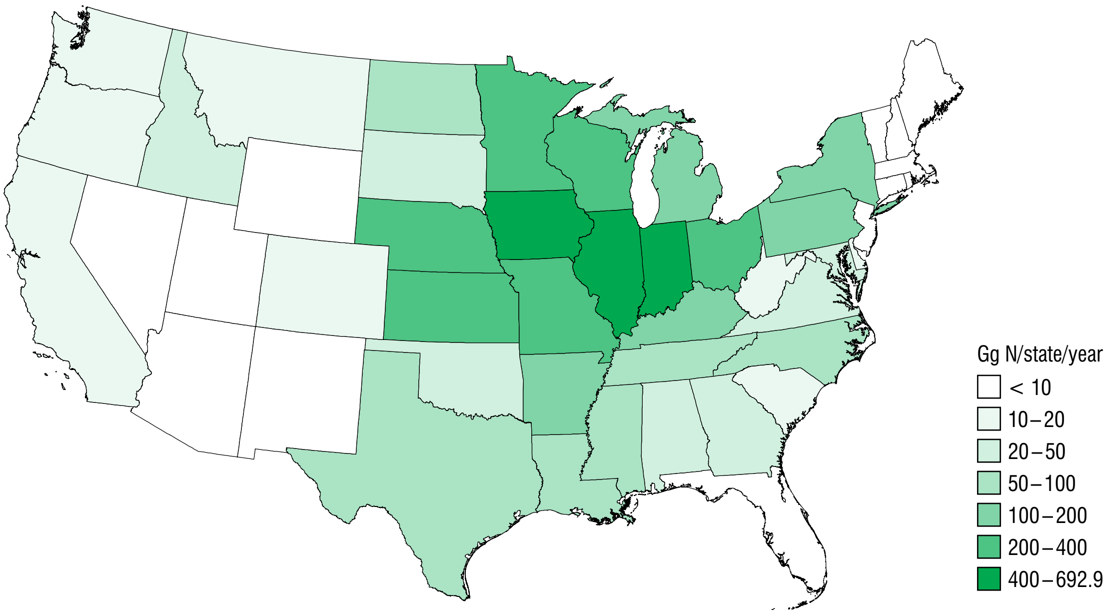
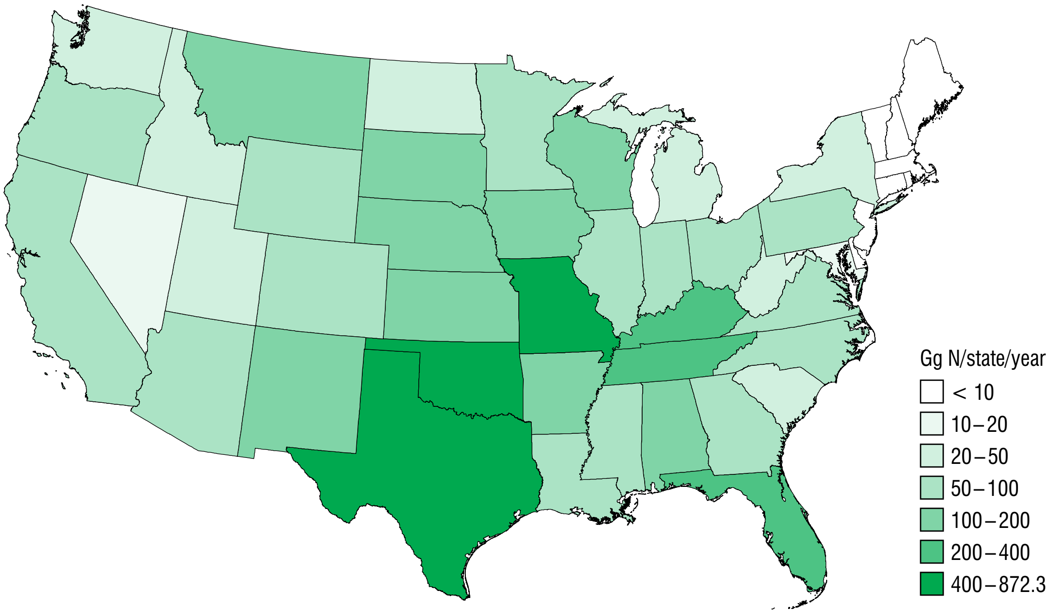


Figure 6-6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, by State, Estimated Using the DAYCENT Model, 1990–2007 (Gg N/year)



Box 6-1: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on a 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 and the environmental conditions at specific locations. Consequently, the Tier 3 approach is likely to produce 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 may enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more refined activity data (e.g., crop-specific N amendment rates), additional data inputs (e.g., 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 the adequacy of the method 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 N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that is likely to create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N added to soils is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

Methodology

The *2006 IPCC Guidelines* (IPCC 2006) divide the Agricultural Soil Management source category into four components: (1) direct emissions due to N additions to cropland and grassland mineral soils, including synthetic fertilizers, sewage sludge applications, crop residues, organic amendments, and biological nitrogen fixation associated with planting of legumes on cropland and grassland soils; (2) direct emissions from drainage and cultivation of organic cropland soils; (3) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (4) indirect emissions from soils and water due to N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

The United States has adopted recommendations from IPCC (2006) on methods for agricultural soil management. These recommendations include (1) estimating the contribution of N from crop residues to indirect soil N_2O emissions; (2) adopting a revised emission factor for direct N_2O emissions to the extent that Tier 1 methods are used in the Inventory (described later in this section); (3) removing double counting of emissions from N-fixing crops associated with the biological N fixation and crop residue N input categories; (4) using revised crop residue statistics to compute N inputs to soils based on harvest yield data; (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation[11] (i.e., computing total emissions from managed land); (6) reporting all emissions from managed lands, largely because management affects all processes leading to soil N_2O emissions. One recommendation from IPCC (2006) has not been adopted: accounting for emissions from pasture renewal, which involves occasional plowing to improve forage production. This practice is not common in the United States, and is not estimated.

The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3, process-based model (DAYCENT) was used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 6-1 for further elaboration). The Tier 1 IPCC (2006) methodology was used to estimate (1) direct emissions from non-major crops on mineral soils (e.g., barley, oats, vegetables, and other crops); (2) the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model (i.e., federal grasslands); and (3) direct emissions from drainage

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[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.

and cultivation of organic cropland soils. Indirect emissions were also estimated with a combination of DAYCENT and the IPCC Tier 1 method.

In past inventory reports, attempts were made to subtract "background" emissions that would presumably occur if the lands were not managed. However, this approach is likely to be inaccurate for estimating the anthropogenic influence on soil N_2O emissions. Moreover, if background emissions could be measured or modeled based on processes unaffected by anthropogenic activity, they would be a very small portion of the total emissions, due to the high inputs of N to agricultural soils from fertilization and legume cropping. Given the recommendation from IPCC (2006) and the influence of management on all processes leading to N_2O emissions from soils in agricultural systems, the decision was made to report total emissions from managed lands for this source category. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

Direct N_2O Emissions from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of major crops—specifically corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton—representing approximately 90 percent of total croplands in the United States. For these croplands, DAYCENT was used to simulate crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005). Note that the influence of land-use change on soil N_2O emissions was not addressed in this analysis, but is a planned improvement.

DAYCENT simulations were conducted for each major crop at the county scale in the United States. Simulating N_2O emissions at the county scale was facilitated by soil and weather data that were available for every county with more than 100 acres of agricultural land, and by land management data (e.g., timing of planting, harvesting, intensity of cultivation) that were available at the agricultural-region level as defined by the Agricultural Sector Model (McCarl et al. 1993). ASM has 63 agricultural regions in the contiguous United States. Most regions correspond to one state, except for those states with greater heterogeneity in agricultural practices; in such cases, more than one region is assigned to a state. While cropping systems were simulated for each county, the results best represent emissions at regional (i.e., state) and national levels due to the regional scale of management data, which include model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested).

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions by anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil for each of these sources was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total of direct N_2O 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 N_2O, regardless of its source, which is unlikely to be the case. However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

DAYCENT was used to estimate direct N_2O emissions due to mineral N available from: (1) the application of synthetic fertilizers; (2) the application of livestock manure; (3) the retention of crop residues (i.e., leaving residues in the field after harvest instead of burning or collecting residues); and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. Note that commercial organic fertilizers are addressed with the Tier 1 method because county-level application data would be needed to simulate applications in the DAYCENT, and currently data are only available at the national scale. The third and fourth sources are generated internally by the DAYCENT model. For the first two practices, annual changes in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), USDA (1966, 1957, 1954, 1946). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA *Economic Research Service Cropping Practices Survey* (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).
- Managed manure production and application to croplands and grasslands: Manure N amendments and daily spread manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). Amendment data for 1997 were scaled to estimate values for other years based on the availability of managed manure N for application to soils in 1997 relative to other years. The amount of available nitrogen from managed manure for each livestock type was calculated as described in the Manure Management section (Section 6.2) and Annex 3.10.
- Retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: 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, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N_2O emissions, but these are not model inputs.
- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2000a) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002). Approximately 3 percent of the crop residues were assumed to be burned based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996), and therefore did not contribute to soil N_2O emissions.

DAYCENT simulations produced per-area estimates of N_2O emissions (g $N_2O\text{-}N/m^2$) for major crops in each county, which were multiplied by the cropland areas in each county to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2008a,b). The emission estimates by reported crop areas in the county were scaled to the regions, and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to interannual variability in weather patterns and other controlling variables, so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions produces more accurate estimates of N_2O emissions than the Tier 1 method.

Non-Major Crop Types on Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types, including barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, rice, peanuts, and other crops that were not included in the DAYCENT simulations. Estimates of direct N_2O emissions from N applications to non-major crop types were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers;[12] and (3) the retention of above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure organic amendments were not included in the DAYCENT simulations because county-level data were not available. Consequently, non-manure organic amendments, as well as manure amendments not included in the DAYCENT simulations, were included in the Tier 1 analysis. The influence of land-use change on soil N_2O emissions from non-major crops has not been addressed in this analysis, but is a planned improvement. The following sources were used to derive activity data:

- A process-of-elimination approach was used to estimate synthetic N fertilizer additions for non-major crops, because little information exists on their fertilizer application rates. The total amount of fertilizer used on farms has been estimated by the USGS from sales records (Ruddy et al. 2006), and these data were aggregated to obtain state-level N additions to farms. After subtracting the portion of fertilizer applied to major crops and grasslands (see sections on Major Crops and Grasslands for information on data sources), the remainder of the total fertilizer used on farms was assumed to be applied to non-major crops.
- A process-of-elimination approach was used to estimate manure N additions for non-major crops, because little information exists on application rates for these crops. The amount of manure N applied to major crops and grasslands was subtracted from total manure N available for land application (see sections on Major Crops and Grasslands for information on data sources), and this difference was assumed to be applied to non-major crops.
- Non-manure, non-sewage-sludge commercial organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content (TVA 1991 through 1994; AAPFCO 1995 through 2008). Manure and sewage sludge components were subtracted from total commercial organic fertilizers to avoid double counting.
- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 1994, 1998, 2003, 2005, 2006, 2008a), 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). Approximately 3 percent of the crop residues were burned and therefore did not contribute to soil N_2O emissions, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC (2006) Tier 1 methods were used to estimate direct N_2O emissions due to drainage and cultivation of organic soils at a state scale. State-scale estimates of the total area of drained and cultivated organic soils were obtained from the *National Resources Inventory* (NRI) (USDA 2000a, as extracted by Eve 2001 and amended by Ogle 2002). Temperature data from Daly et al. (1994, 1998) were used to subdivide areas into temperate and tropical climates using the climate classification from IPCC (2006).

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[12] Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer have been excluded to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands.

Data were available for 1982, 1992 and 1997. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions (IPCC 2006).

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 method described in IPCC (2006) were combined to estimate emissions from grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, which may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate county-scale N_2O emissions from 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), and synthetic fertilizer application. Other N inputs were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the section for Major Crop Types on Mineral Cropland Soils. Managed manure N amendments to grasslands were 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 6.2) and annex (Annex 3.10). Biological N fixation is simulated within DAYCENT and therefore was not an input to the model.

Manure N deposition from grazing animals (i.e., PRP manure) was an input to the DAYCENT model (see Annex 3.10), and included approximately 91 percent of total PRP manure. The remainder of the PRP manure N excretions in each county was assumed to be excreted on federal grasslands (i.e., DAYCENT simulations were only conducted for non-federal grasslands), and the N_2O emissions were estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. The amounts of PRP manure N applied on non-federal and federal grasslands in each county were based on the proportion of non-federal grassland area according to data from the NRI (USDA 2000a), relative to the area of federal grasslands from the National Land Cover Dataset (Vogelman et al. 2001).

Sewage sludge was 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 was estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007). Sewage sludge data on soil amendments on agricultural lands were only available at the national scale, and it was 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 N_2O emissions from grassland soils, and consequently, emissions from sewage sludge were estimated using the IPCC (2006) Tier 1 method.

DAYCENT simulations produced per-area estimates of N_2O emissions (g N_2O-N/m^2) for pasture and rangelands, which were multiplied by the reported pasture and rangeland areas in each county. Grassland area data were obtained from the NRI (USDA 2000a). The 1997 NRI area data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2007, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994. The county estimates were scaled to the 63 agricultural regions, and the national estimate was calculated by summing results across all regions. Tier 1 estimates of N_2O emissions for the PRP manure N applied to non-federal lands and sewage sludge N were produced by multiplying the N input by the appropriate emission factor.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from major and non-major crops on mineral cropland soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 6-15 and Table 6-16).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types

This section describes the methods used for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). 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 asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter, and asymbiotic fixation. The nitrate 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, grasslands, forest lands, and settlements.

Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N from Managed Soils

Similarly to the direct emissions calculation, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 methods were combined to estimate the amount of N that was transported from croplands, grasslands, forest lands, and settlements through volatilization, and eventually emitted as N_2O. DAYCENT was used to estimate N volatilization for land areas whose direct emissions were simulated with DAYCENT (i.e., major croplands and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the sections on major crops and grasslands. The Tier 1 method and default IPCC fractions for N subject to volatilization were used for areas and N applications that were not simulated with DAYCENT (i.e., N inputs on non-major croplands, PRP manure N excretion on federal grasslands, sewage sludge application on grasslands). The Tier 1 method and default fractions were also used to estimate N subject to volatilization from N inputs on settlements and forest lands (see the Land Use, Land-Use Change, and Forestry chapter). With the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with the amount of volatilized N (Table 6-18).

Indirect N_2O from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DAYCENT model and IPCC (2006) Tier 1 method were combined to estimate the amount of N that was transported from croplands, grasslands, forest lands, and settlements through leaching and surface runoff into water bodies, and eventually emitted as N_2O. DAYCENT was used to simulate the amount of N transported from lands used to produce major crops and most grasslands. Nitrogen transport from all other areas was 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 produce non-major crops, sewage sludge amendments on grasslands, PRP manure N excreted on federal grasslands, and N inputs on settlements and forest lands. For both the DAYCENT and IPCC (2006) Tier 1 methods, nitrate leaching was assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation did not exceed the potential evapotranspiration, as recommended by IPCC (2006). With both the DAYCENT and Tier 1 approaches, the IPCC (2006) default emission factor was used to estimate indirect N_2O emissions associated with N losses through leaching and runoff (Table 6-18).

Uncertainty

Uncertainty was estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT; (2) the components of indirect emissions (N volatilized and leached or runoff) calculated by DAYCENT; (3) direct emissions calculated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) calculated with the IPCC (2006) Tier 1 method; and (5) indirect emissions calculated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions, which

Table 6-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2007 ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate ($Tg\ CO_2$ Eq.)		Uncertainty Range Relative to Emission Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	172.0	126.2	265.2	-27%	+54%
Indirect Soil N_2O Emissions	N_2O	35.9	20.6	84.8	-43%	+136%

Note: Due to lack of data, uncertainties in areas for major crops, managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

account for the majority of N_2O emissions from agricultural management, as well as the components of indirect emissions calculated by DAYCENT were estimated with a Monte Carlo Analysis, addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization). Uncertainties in direct emissions calculated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions were estimated with a simple error propagation approach (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.11.

Uncertainties from the Tier 1 and Tier 3 (i.e., DAYCENT) estimates were combined using simple error propagation (IPCC 2006), and the results are summarized in Table 6-19. Agricultural direct soil N_2O emissions in 2007 were estimated to be between 126.2 and 265.2 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 27 percent below and 54 percent above the 2007 emission estimate of 172.0 Tg CO_2 Eq. The indirect soil N_2O emissions in 2007 were estimated to range from 20.5 to 84.8 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 43 percent below and 136 percent above the 2007 emission estimate of 35.9 Tg CO_2 Eq.

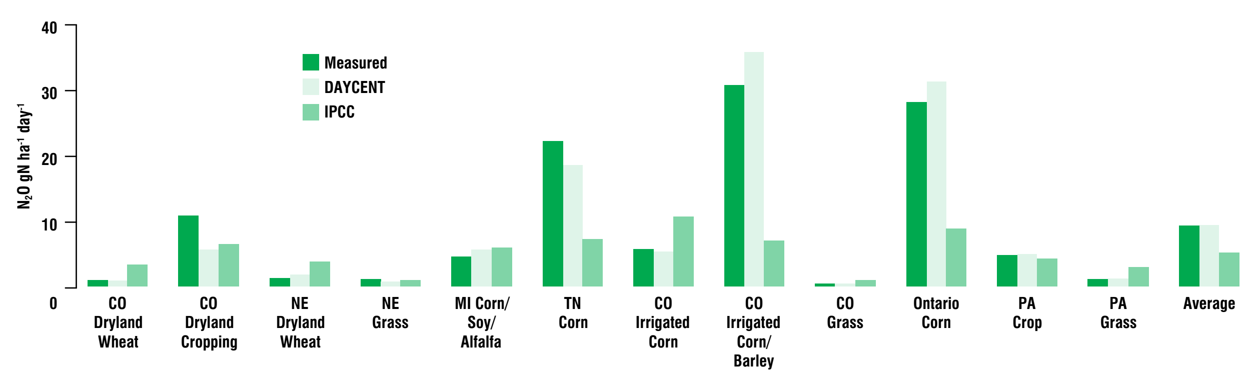
QA/QC and Verification

For quality control, DAYCENT results for N_2O emissions and NO_3^- leaching were compared with field data representing various cropped/grazed systems, soil types, and climate patterns (Del Grosso et al. 2005, Del Grosso et al. 2008), and further evaluated by comparing to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data were available for 11 sites in the United States and one in Canada, representing 30 different combinations of fertilizer treatments and cultivation practices. DAYCENT estimates of N_2O emissions were closer to measured values at all sites except for Colorado dryland cropping (Figure 6-7). In general, 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 are less biased. This is not surprising because DAYCENT accounts for site-level factors (weather, soil type) that influence N_2O emissions. NO_3^- leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.89 and 0.94 for annual N_2O emissions and NO_3^- leaching, respectively. This comparison demonstrates that DAYCENT provides relatively high predictive capability for N_2O emissions and NO_3^- leaching, and is an improvement over the IPCC Tier 1 method (see additional information in Annex 3.11).

Spreadsheets containing input data and probability distribution functions required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as well as the program scripts that were used to run the Monte Carlo uncertainty analysis. Several errors were identified following re-organization of the calculation spreadsheets, and corrective actions have been taken. In particular, some of the links between spreadsheets were missing or needed to be modified. Spreadsheets containing input data, emission factors, and calculations required for the Tier 1 approach were checked and no errors were found.

Figure 6-7

Comparison of Measured Emissions at Field Sites with Modeled Emissions Using the DAYCENT Simulation Model



Recalculations Discussion

Several revisions were made in the Agricultural Soil Management Section for the current Inventory.

First, a new version of the DAYCENT model was made operational for the Inventory. This version of DAYCENT has several improvements, including elimination of the influence of labile (i.e., easily decomposable by microbes) C availability on surface litter denitrification rates, incorporation of precipitation events as a controlling variable on surface litter denitrification, and allowing the wettest soil layer within the rooting zone to control plant transpiration.

Second, given a new operational version of DAYCENT, the structural uncertainty in the model was re-evaluated and estimates were revised from the previous Inventory. In the current application, residual error from the linear mixed-effect model was also included as a component of the structural uncertainty, and this led to a larger uncertainty in the N_2O emission estimates from DAYCENT. This component was not addressed in the previous Inventory because it was considered measurement error. However, some of the residual error is likely associated with the structure of the model. In addition, structural uncertainty was evaluated in the grassland predictions from DAYCENT, which had not been included in the previous Inventory.

Third, PRP manure N deposition on non-federal grasslands was estimated from county-level grazing animal population data, instead of using estimates of N deposition computed internally in the DAYCENT model. Quality control on the previous Inventory suggested that DAYCENT over-estimated PRP manure N deposition in some states. This improvement ensures that the data on PRP manure N in the DAYCENT model simulations is consistent with N excretion data from the Manure Management section of this Inventory.

Fourth, nitrate leaching was assumed to be an insignificant source of indirect N_2O in cropland and grassland systems where the amount of precipitation plus irrigation did not exceed the potential evapotranspiration, as recommended by IPCC (2006). These areas are typically semi-arid to arid, and nitrate leaching to groundwater is a relatively uncommon event. Adopting this recommendation reduced indirect N_2O emissions.

The recalculations associated with these changes reduced emissions by about 23 percent on average, primarily due to the new operational version of DAYCENT, revised structural uncertainty associated with the model, and reduced impact of N leaching on indirect N_2O emissions in arid and semi-arid regions. Earlier versions of DAYCENT tended to over-estimate emissions above 6 g N_2O/m^2, and although these emissions were adjusted using the structural uncertainty estimator, there was considerable uncertainty in those adjustments. The new operational version of DAYCENT does not overestimate N_2O emissions for the majority of crops, with the exception of small grains.

Including residual error from the linear mixed-effect model as a component of the structural uncertainty and structural uncertainty in the grassland predictions from DAYCENT resulted in wider 95 percent confidence intervals compared to the previous Inventory. Of these changes, including structural uncertainty in the grassland predictions from DAYCENT was responsible for most of the increase in uncertainty.

Planned Improvements

Several improvements are planned for the Agricultural Soil Management sector. The first improvement is to incorporate more land-use survey data from the NRI (USDA 2000a) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1979 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records in the current Inventory, and there are three major disadvantages to this. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, which is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI provides a complete history of cropland areas for four out of every five years from 1979 to 1997, and then every year after 1998. Third, the current Inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil Management methods more consistent with the methods used to estimate C stock changes for agricultural soils. The structure of model input files that contain land management data will need to be extensively revised to facilitate use of the annualized NRI data. This improvement is planned to take place over the next several years.

Other planned improvements are minor but will lead to more accurate estimates, including updating DAYMET weather data for more recent years, setting the PRP emission factor for horse, sheep and goats to 0.01 in accordance with guidance from IPCC (2006) and using a rice-crop-specific EF for N amendments to rice areas.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field; composted and then applied to soils; landfilled; or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. Field burning of crop residues is not considered a net source of CO_2, because the C released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. It is assumed that 3 percent of the residue for each of these crops is burned each year, except for rice.[13] In 2007, CH_4 and N_2O emissions from field burning were 0.9 Tg CO_2 Eq. (42 Gg) and 0.5 Tg. CO_2 Eq. (2 Gg), respectively. Annual emissions from this source over the period 1990 to 2007 have remained relatively constant, averaging approximately 0.8 Tg CO_2 Eq. (37 Gg) of CH_4 and 0.4 Tg CO_2 Eq. (1 Gg) of N_2O (see Table 6-20 and Table 6-21).

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[13] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Table 6-20: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1995	2000	2005	2006	2007
CH_4	**0.7**	**0.7**	**0.8**	**0.9**	**0.8**	**0.9**
Wheat	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	0.3	0.3	0.4	0.4	0.4	0.5
Barley	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**
Wheat	+	+	+	+	+	+
Rice	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+
Soybeans	0.2	0.2	0.3	0.3	0.3	0.2
Peanuts		+	+	+	+	+
Total	**1.1**	**1.0**	**1.3**	**1.4**	**1.3**	**1.4**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-21: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	1995	2000	2005	2006	2007
CH_4	**33**	**32**	**38**	**41**	**39**	**42**
Wheat	7	5	5	5	4	5
Rice	4	4	4	5	4	4
Sugarcane	1	1	1	1	1	1
Corn	13	13	17	19	18	22
Barley	1	1	1	+	+	+
Soybeans	7	8	10	11	12	9
Peanuts	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**2**	**2**	**2**
Wheat	+	+	+	+	+	+
Rice	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+
Corn	+	+	+	+	+	+
Barley	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+
CO	**691**	**663**	**792**	**860**	**825**	**892**
NO_x	**28**	**29**	**35**	**39**	**38**	**37**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The Tier 2 methodology used for estimating greenhouse gas emissions from field burning of agricultural residues in the United States is consistent with IPCC (2006) (for more details, see Box 6-2). In order to estimate the amounts of C and nitrogen (N) released during burning, the following equation was used:[14]

C or N released = Σ over all crop types
(Crop Production × Residue/Crop Ratio ×
Dry Matter Fraction × Fraction of Residue Burned ×
Burning Efficiency × Combustion Efficiency ×
Fraction of C or N)

where,

Crop Production = Annual production of crop in Gg

Residue/Crop Ratio = Amount of residue produced per unit of crop production

Fraction of Residue Burned = Amount of residue that is burned per unit of total residue

Dry Matter Fraction = Amount of dry matter per unit of biomass

Fraction of C or N = Amount of C or N per unit of dry matter

Burning Efficiency = The proportion of prefire fuel biomass consumed[15]

Combustion Efficiency = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively[15]

The amount C or N released was used in the following equation to determine the CH_4, CO, N_2O and NO_x emissions from the field burning of agricultural residues:

CH_4 and CO, or N_2O and NO_x Emissions from Field
Burning of Agricultural Residues = (C or N Released) ×
(Emissions Ratio for C or N) × (Conversion Factor)

where,

Emissions Ratio = g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released

Conversion Factor = conversion, by molecular weight ratio, of CH_4 to C (16/12), or CO to C (28/12), or N_2O to N (44/28), or NO_x to N (30/14)

The types of crop residues burned in the United States were determined from various state-level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's Field Crops, Final Estimates 1987–1992, 1992–1997, 1997–2002 (USDA 1994, 1998, 2003), and Crop Production Summary (USDA 2005 through 2008). Rice production data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007a, 2008), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005, 2006) were applied to Oklahoma acreages[16] (Lee 2003 through 2006; Anderson 2008). The production data for the crop types whose residues are burned are presented in Table 6-22.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level annual rice production statistics. The annual percentages of rice area burned in each state were obtained from agricultural extension agents in each state and reports of the California Air Resources Board (Anonymous 2006; Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Guethle 2007, 2008; Klosterboer

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[14] As is explained later in this section, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[15] 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).

[16] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

1999a, 1999b, 2000 through 2003; Lancero 2006 through 2008; Lee 2005 through 2007; Lindberg 2002 through 2005; Linscombe 1999a, 1999b, 2001 through 2008; Najita 2000, 2001; Sacramento Valley Basinwide Air Pollution Control Council 2005, 2007; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001 through 2003; Texas Agricultural Experiment Station 2006 through 2008; Walker 2004 through 2008; Wilson 2003 through 2007) (see Table 6-23). The estimates provided for Florida remained constant over the entire 1990 through 2007 period. While the estimates for all other states varied over the time series, estimates for Missouri remained constant through 2005, dropped in 2006, and remained constant at the 2006 value in 2007. For California, the annual percentages of rice area burned in the Sacramento Valley are assumed to be representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These values generally declined between 1990 and 2007 because of a legislated reduction in rice straw burning (Lindberg 2002), although there was a slight increase from 2004 to 2005 and from 2006 to 2007 (see Table 6-23).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The data for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue C contents and N contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue C content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The N content of peanuts is from Ketzis (1999). These data are listed in Table 6-24. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios and conversion factors for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-22: Agricultural Crop Production (Gg of Product)

Crop	1990	1995	2000	2005	2006	2007
Wheat	74,292	59,404	60,641	57,280	49,316	56,247
Rice	7,114	7,947	8,705	10,150	8,813	8,979
Sugarcane	25,525	27,922	32,762	24,137	26,820	27,972
Corn[a]	201,534	187,970	251,854	282,311	267,598	332,092
Barley	9,192	7,824	6,919	4,613	3,923	4,612
Soybeans	52,416	59,174	75,055	83,368	86,770	70,358
Peanuts	1,635	1,570	1,481	2,209	1,571	1,697

[a] Corn for grain (i.e., excludes corn for silage).

Box 6-2: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

This Inventory calculates emissions from Burning of Agricultural Residues using a Tier 2 methodology that is based on IPCC/UNEP/OECD/IEA (1997) and incorporates crop- and country-specific emission factors and variables. The equation used in this Inventory varies slightly in form from the one presented in the IPCC (2006) guidelines, but both equations rely on the same underlying variables. The IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues. IPCC (2006) default factors are provided only for four crops (wheat, corn, rice, and sugarcane), while this Inventory analyzes emissions from seven crops. A comparison of the methods and factors used in (1) the current Inventory and (2) the default IPCC (2006) approach was undertaken to determine the magnitude of the difference in overall estimates resulting from the two approaches. Since the default IPCC (2006) approach calls for area burned data that are currently unavailable for the United States, estimates of area burned were developed using USDA data on area harvested for each crop multiplied by the estimated fraction of residue burned for that crop (see Table 6-24).

The IPCC (2006) default approach resulted in 19 percent higher emissions of CH_4 and 35 percent higher emissions of N_2O than the current estimates in this Inventory. It is reasonable to maintain the current methodology, since the IPCC (2006) defaults are only available for four crops and are worldwide average estimates, while current inventory estimates are based on U.S.-specific, crop-specific, published data.

Table 6-25: 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_2O: N	0.007[b]	44/28
NO_x: N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).

[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

Uncertainty

A significant source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops and among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. Based on expert judgment, uncertainty in the fraction of crop residue burned ranged from zero to 100 percent, depending on the state and crop type.

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-26. Methane emissions

Table 6-24: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/ Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency	Combustion Efficiency
Wheat	1.3	0.03	0.93	0.4428	0.0062	0.93	0.88
Rice	1.4	Variable	0.91	0.3806	0.0072	0.93	0.88
Sugarcane	0.8	0.03	0.62	0.4235	0.0040	0.93	0.88
Corn	1.0	0.03	0.91	0.4478	0.0058	0.93	0.88
Barley	1.2	0.03	0.93	0.4485	0.0077	0.93	0.88
Soybeans	2.1	0.03	0.87	0.4500	0.0230	0.93	0.88
Peanuts	1.0	0.03	0.86	0.4500	0.0106	0.93	0.88

Table 6-26: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.9	0.2	1.7	-73%	+94%
Field Burning of Agricultural Residues	N_2O	0.5	0.1	0.9	-73%	+85%

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

from field burning of agricultural residues in 2007 were estimated to be between 0.2 and 1.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 73 percent below and 94 percent above the 2007 emission estimate of 0.9 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.1 and 0.9 Tg CO_2 Eq. (or approximately 73 percent below and 85 percent above the 2007 emission estimate of 0.5 Tg CO_2 Eq.).

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

The crop production data for 2006 and 2007 were updated using data from USDA (2008). This change resulted in an increase in the CH_4 emission estimate for 2006 of 0.01 percent, and an increase in the N_2O emission estimate for 2006 of 0.002 percent, relative to the previous Inventory.

Planned Improvements

The estimated 3 percent of crop residue burned for all crops, except rice, is based on data gathered from several state greenhouse gas inventories. This fraction is the most statistically significant input to the emissions equation, and an important area for future improvement. More crop- and state-specific information on the fraction burned will be investigated by literature review and/or by contacting state departments of agriculture.

Preliminary research on agricultural burning in the United States indicates that residues from several additional crop types (e.g., grass for seed, blueberries, and fruit and nut trees) are burned. Whether sufficient information exists for inclusion of these additional crop types in future Inventories is being investigated. The extent of recent state crop-burning regulations is also being investigated.

7. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the net greenhouse gas flux[1] resulting from the uses and changes in land types and forests in the United States. 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, and settlements (as well as wetlands). The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported using estimates of changes in forest carbon (C) stocks, non-carbon dioxide (CO_2) emissions from forest fires, and the application of synthetic fertilizers to forest soils. The greenhouse gas flux reported in this chapter from agricultural lands (i.e., cropland and grassland) includes changes in organic C stocks in mineral and organic soils due to land use and management, and emissions of CO_2 due to the application of crushed limestone and dolomite to managed land (i.e., soil liming) and urea fertilization. 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*. Fluxes resulting from *Settlements Remaining Settlements* include those from urban trees and soil fertilization. Landfilled yard trimmings and food scraps are accounted for separately under Other.

The estimates in this chapter, with the exception of CO_2 fluxes from wood products and urban trees, and CO_2 emissions from liming and urea fertilization, are based on activity data collected at multiple-year intervals, which are in the form of forest, land-use, and municipal solid waste surveys. CO_2 fluxes from forest C stocks (except the wood product components) and from agricultural soils (except the liming component) are calculated on an average annual basis from data collected in intervals ranging from 1 to 10 years. The resulting annual averages are applied to years between surveys. Calculations of non-CO_2 emissions from forest fires are based on forest CO_2 flux data. For the landfilled yard trimmings and food scraps source, periodic solid waste survey data were interpolated so that annual storage estimates could be derived. This flux has been applied to the entire time series, and periodic U.S. census data on changes in urban area have been used to develop annual estimates of CO_2 flux.

Land use, land-use change, and forestry activities in 2007 resulted in a net C sequestration of 1,062.6 Tg CO_2 Eq. (289.8 Tg C) (Table 7-1 and Table 7-2). This represents an offset of approximately 17.4 percent of total U.S. CO_2 emissions. Total land use, land-use change, and forestry net C sequestration[2] increased by approximately 26 percent between 1990 and 2007. This increase was primarily due to an increase in the rate of net C accumulation in forest C stocks. Net C accumulation in *Forest Land Remaining Forest Land*, *Land Converted to Grassland*, and *Settlements Remaining Settlements* increased, while net C

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[1] The term "flux" is used here to encompass both emissions of greenhouse gases to the atmosphere, and removal of C from the atmosphere. Removal of C from the atmosphere is also referred to as "carbon sequestration."

[2] 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 act as a sink. This is also referred to as net C sequestration.

Table 7-1: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Sink Category	1990	1995	2000	2005	2006	2007
Forest Land Remaining Forest Land[a]	(661.1)	(686.6)	(512.6)	(975.7)	(900.3)	(910.1)
Cropland Remaining Cropland	(29.4)	(22.9)	(30.2)	(18.3)	(19.1)	(19.7)
Land Converted to Cropland	2.2	2.9	2.4	5.9	5.9	5.9
Grassland Remaining Grassland	(46.7)	(36.4)	(51.4)	(4.6)	(4.6)	(4.7)
Land Converted to Grassland	(22.3)	(22.5)	(32.0)	(26.7)	(26.7)	(26.7)
Settlements Remaining Settlements[b]	(60.6)	(71.5)	(82.4)	(93.3)	(95.5)	(97.6)
Other (Landfilled Yard Trimmings and Food Scraps)	(23.5)	(13.9)	(11.3)	(10.2)	(10.4)	(9.8)
Total	**(841.4)**	**(851.0)**	**(717.5)**	**(1,122.7)**	**(1,050.5)**	**(1,062.6)**

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.
Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 7-2: Net CO_2 Flux from Carbon Stock Changes in Land Use, Land-Use Change, and Forestry (Tg C)

Sink Category	1990	1995	2000	2005	2006	2007
Forest Land Remaining Forest Land[a]	(180.3)	(187.2)	(139.8)	(266.1)	(245.5)	(248.2)
Cropland Remaining Cropland	(8.0)	(6.3)	(8.2)	(5.0)	(5.2)	(5.4)
Land Converted to Cropland	0.6	0.8	0.6	1.6	1.6	1.6
Grassland Remaining Grassland	(12.7)	(9.9)	(14.0)	(1.3)	(1.3)	(1.3)
Land Converted to Grassland	(6.1)	(6.1)	(8.7)	(7.3)	(7.3)	(7.3)
Settlements Remaining Settlements[b]	(16.5)	(19.5)	(22.5)	(25.4)	(26.0)	(26.6)
Other (Landfilled Yard Trimmings and Food Scraps)	(6.4)	(3.8)	(3.1)	(2.8)	(2.8)	(2.7)
Total	**(229.5)**	**(232.1)**	**(195.7)**	**(306.2)**	**(286.5)**	**(289.8)**

[a] Estimates include C stock changes on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[b] Estimates include C stock changes on both *Settlements Remaining Settlements* and *Land Converted to Settlements*.
Note: 1 Tg C = 1 teragram C = 1 million metric tons C. Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

accumulation in *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, and landfilled yard trimmings and food scraps slowed over this period. Emissions from *Land Converted to Cropland* increased between 1990 and 2007.

Emissions from Land Use, Land-Use Change, and Forestry are shown in Table 7-3 and Table 7-4. Liming of agricultural soils and urea fertilization in 2007 resulted in CO_2 emissions of 4.1 Tg CO_2 Eq. (4,055 Gg) and 4.0 Tg CO_2 Eq. (3,952 Gg), respectively. Lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) resulted in CO_2 emissions of 1.0 Tg CO_2 Eq. (1,010 Gg), and N_2O emissions of less than 0.01 Tg CO_2 Eq. The application of synthetic fertilizers to forest and settlement soils in 2007 resulted in direct N_2O emissions of 1.9 Tg CO_2 Eq. (6 Gg). Direct N_2O emissions from fertilizer application to forest soils have increased by a multiple of 6.7 since 1990, but still account for a relatively small portion of overall emissions at 0.3 Tg CO_2 Eq. (1 Gg) in 2007. Forest fires in 2007 resulted in methane (CH_4) emissions of 29.0 Tg CO_2 Eq. (1,381 Gg), and in N_2O emissions of 2.9 Tg CO_2 Eq. (9 Gg).

Table 7-3: Emissions from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Source Category	1990	1995	2000	2005	2006	2007
CO_2	**8.1**	**8.1**	**8.8**	**8.9**	**8.8**	**9.0**
Cropland Remaining Cropland: Liming of Agricultural Soils	4.7	4.4	4.3	4.3	4.2	4.1
Urea Fertilization	2.4	2.7	3.2	3.5	3.7	4.0
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1.0	1.0	1.2	1.1	0.9	1.0
CH_4	**4.6**	**6.1**	**20.6**	**14.2**	**31.3**	**29.0**
Forest Land Remaining Forest Land: Forest Fires	4.6	6.1	20.6	14.2	31.3	29.0
N_2O	**1.5**	**2.0**	**3.6**	**3.3**	**5.0**	**4.9**
Forest Land Remaining Forest Land: Forest Fires	0.5	0.6	2.1	1.4	3.2	2.9
Forest Land Remaining Forest Land: Forest Soils[a]	+	0.1	0.3	0.3	0.3	0.3
Settlements Remaining Settlements: Settlement Soils[b]	1.0	1.2	1.2	1.5	1.5	1.6
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+
Total	**14.2**	**16.2**	**33.0**	**26.4**	**45.1**	**42.9**

+ Less than 0.05 Tg CO_2 Eq.

[a] 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.

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements,* and *Land Converted to Settlements,* but not from land-use conversion.

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter.

Totals may not sum due to independent rounding.

Table 7-4: Emissions from Land Use, Land-Use Change, and Forestry (Gg)

Source Category	1990	1995	2000	2005	2006	2007
CO_2	**8,117**	**8,067**	**8,768**	**8,933**	**8,768**	**9,018**
Cropland Remaining Cropland: Liming of Agricultural Soils	4,667	4,392	4,328	4,349	4,233	4,055
Urea Fertilization	2,417	2,657	3,214	3,504	3,656	3,952
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	1,033	1,018	1,227	1,079	879	1,010
CH_4	**218**	**293**	**983**	**676**	**1,489**	**1,381**
Forest Land Remaining Forest Land: Forest Fires	218	293	983	676	1,489	1,381
N_2O	**5**	**6**	**12**	**11**	**16**	**16**
Forest Land Remaining Forest Land: Forest Fires	2	2	7	5	10	9
Forest Land Remaining Forest Land: Forest Soils[a]	+	+	1	1	1	1
Settlements Remaining Settlements: Settlement Soils[b]	3	4	4	5	5	5
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+

+ Less than 0.5 Gg

[a] 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.

[b] Estimates include emissions from N fertilizer additions on both *Settlements Remaining Settlements,* and *Land Converted to Settlements,* but not from land-use conversion.

Note: These estimates include direct emissions only. Indirect N_2O emissions are reported in the Agriculture chapter.

Totals may not sum due to independent rounding.

7.1. 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, (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series associated with the greenhouse gas inventory, such that increases in the land areas within particular land use categories are balanced by decreases in the land areas of other categories, and (3) account for greenhouse gas fluxes on all managed lands. The implementation of such a system helps to ensure that estimates of greenhouse gas fluxes are as accurate as possible. This section of the National Greenhouse Gas Inventory has been developed in order to comply with this guidance.

Multiple databases are utilized to track land management in the United States, which are also used as the basis to categorize the land area into the six IPCC land-use categories (i.e., *Forest Land Remaining Forest Land*, *Cropland Remaining Cropland*, *Grassland Remaining Grassland*, *Wetlands Remaining Wetlands*, *Settlements Remaining Settlements* and *Other Land Remaining Other Land*) and thirty land-use change categories (e.g., *Cropland Converted to Forest Land*, *Grassland Converted to Forest Land, Wetlands Converted to Forest Land, Settlements Converted to Forest Land, Other Land Converted to Forest Lands*)[3] (IPCC 2006). The primary databases are the U.S. Department of Agriculture (USDA) *National Resources Inventory* (NRI)[4] and the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[5] Database. The U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD)[6] is also used to identify land uses in regions that were not included in the NRI or FIA. The total land area included in the U.S. Inventory is 786 million hectares, and this entire land base is considered managed.[7] In 1990, the United States had a total of 244 million hectares of Forest Land, 171 million hectares of Cropland, 288 million hectares of Grassland, 28 million hectares of Wetlands, 40 million hectares of Settlements, and 14 million hectares in the Other Land[8] category (Table 7-5). By 2007, the total area in Forest Land had increased by 3.7 percent to 253 million hectares, Cropland had declined by 4.0 percent to 163 million hectares, Grassland declined by 3.5 percent to 278 million hectares, Wetlands decreased by 2.4 percent to 28 million hectares, Settlements increased by 22.6 percent to 49 million hectares, and Other Land remained at about 14 million hectares.

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 fifty states (Figure 7-1). 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. 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.

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[3] Land-use category definitions are provided in the Methodology section.

[4] NRI data is available at <http://www.ncgc.nrcs.usda.gov/products/nri/index.html>.

[5] FIA data is available at <http://fia.fs.fed.us/tools-data/data/>.

[6] NLCD data is available at <http://www.mrlc.gov/>.

[7] The current land representation does not include areas from Alaska, U.S. territories or federal lands in Hawaii, but there are planned improvements to include these regions in future reports.

[8] Other Land is a miscellaneous category that includes lands that are not classified into the other five land-use categories. It also allows the total of identified land areas to match the national area.

Table 7-5: Land Use, Land-Use Change, and Forestry on Managed Land (Thousands of Hectares)

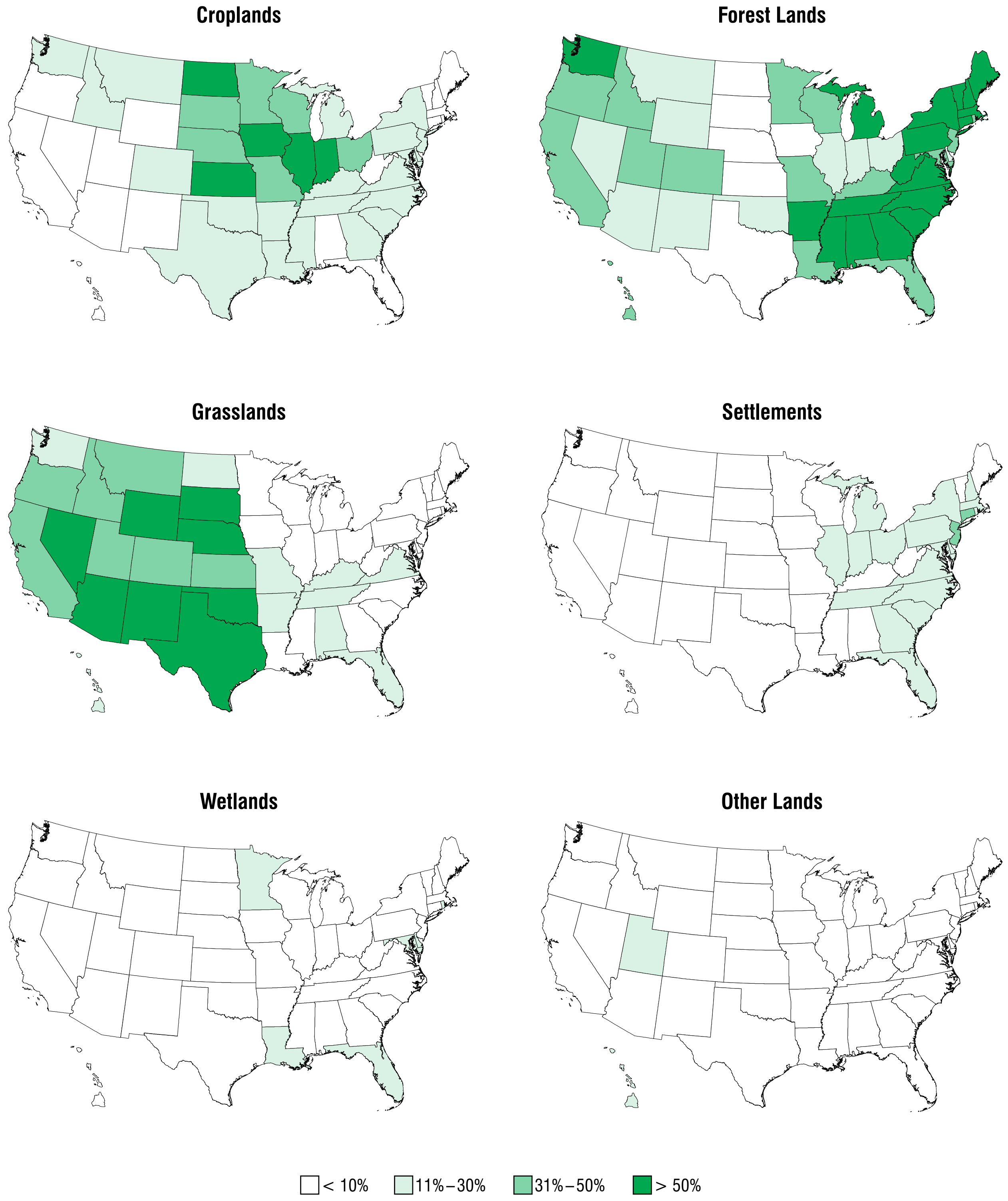
Land Use, Land-Use Change Categories	1990	1995	2000	2005	2006	2007
Total Forest Land	**243,160**	**246,363**	**248,993**	**251,441**	**252,252**	**252,927**
Forest Land Remaining Forest Land	238,088	237,767	235,855	238,335	239,111	239,755
Cropland Converted to Forest Land	1,147	1,804	2,842	2,863	2,871	2,878
Grassland Converted to Forest Land	3,401	5,802	8,691	8,574	8,600	8,623
Wetlands Converted to Forest Land	58	125	193	192	193	194
Settlements Converted to Forest Land	98	179	278	288	289	290
Other Lands Converted to Forest Land	368	686	1,135	1,188	1,188	1,188
Total Cropland	**170,677**	**168,501**	**163,914**	**163,236**	**163,195**	**163,183**
Cropland Remaining Cropland	155,478	149,353	143,816	145,573	145,533	145,522
Forest Land Converted to Cropland	1,105	1,289	1,027	806	805	805
Grassland Converted to Cropland	13,298	16,517	17,623	15,514	15,513	15,513
Wetlands Converted to Cropland	163	249	267	234	234	234
Settlements Converted to Cropland	470	869	889	825	825	825
Other Lands Converted to Cropland	162	223	293	283	283	283
Total Grassland	**289,333**	**284,622**	**281,748**	**279,282**	**278,762**	**278,273**
Grassland Remaining Grassland	279,318	270,985	262,679	261,555	261,105	260,676
Forest Land Converted to Grassland	1,514	2,129	3,136	2,858	2,846	2,837
Cropland Converted to Grassland	7,873	10,506	14,585	13,517	13,463	13,415
Wetlands Converted to Grassland	233	352	359	345	344	343
Settlements Converted to Grassland	133	237	276	270	269	268
Other Lands Converted to Grassland	262	413	712	738	735	734
Total Wetlands	**28,545**	**28,266**	**28,456**	**28,151**	**27,960**	**27,817**
Wetlands Remaining Wetlands	27,892	27,298	26,907	26,591	26,408	26,272
Forest Land Converted to Wetlands	140	253	406	415	412	409
Cropland Converted to Wetlands	139	233	371	363	360	358
Grassland Converted to Wetlands	322	456	726	736	734	732
Settlements Converted to Wetlands	<1	<1	3	3	3	3
Other Land Converted to Wetlands	51	25	43	43	43	43
Total Settlements	**39,548**	**43,351**	**48,160**	**49,285**	**49,255**	**49,248**
Settlements Remaining Settlements	34,772	34,378	33,999	35,011	34,982	34,975
Forest Land Converted to Settlements	1,842	3,561	5,777	5,873	5,873	5,873
Cropland Converted to Settlements	1,373	2,518	3,738	3,673	3,673	3,672
Grassland Converted to Settlements	1,498	2,756	4,397	4,479	4,479	4,479
Wetlands Converted to Settlements	3	9	31	32	32	32
Other Land Converted to Settlements	60	128	218	217	217	217
Total Other Land	**14,425**	**14,584**	**14,427**	**14,304**	**14,275**	**14,250**
Other Land Remaining Other Land	13,437	12,895	12,171	12,061	12,033	12,009
Forest Land Converted to Other Land	193	321	545	560	559	559
Cropland Converted to Other Land	279	385	473	499	499	499
Grassland Converted to Other Land	458	888	1,105	1,058	1,057	1,057
Wetlands Converted to Other Land	55	88	123	114	114	114
Settlements Converted to Other Land	3	7	11	12	12	12
Grand Total[a]	**785,687**	**785,687**	**785,698**	**785,698**	**785,698**	**785,698**

[a] The total land changes over time because there is a net transfer of land from federal to non-federal ownership in Hawaii. Federal lands in Hawaii are not currently included in the U.S. Land Representation, leading to a change in the land base over time. There is a planned improvement to include land-use data for federal lands in Hawaii, which will resolve the issue with a changing land base over time. In addition, area data for Hawaii are currently only available through 1997 leading to no change in the federal land base after 1997.

Note: Managed and unmanaged lands are not differentiated in the current U.S. Land Representation Assessment. In addition, U.S. Territories along with federal lands in Hawaii have not been classified into land uses and are not included in the U.S. land representation assessment. See planned improvements for discussion on plans to include Alaska, territories and federal lands in Hawaii in future Inventories.

Figure 7-1

Percent of Total Land Area in the General Land Use Categories for 2007



Note: Land use/land-use change categories were aggregated into the 6 general land-use categories based on the current use in 2007.

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 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, grassland to cropland, etc.), using surveys or other forms of data that do not provide location data on specific parcels of land. Approach 3 extends Approach 2 by providing location data on specific 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 the 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. All of these datasets have a spatially-explicit time series of land-use data, and therefore Approach 3 is used to provide a full representation of land use in the U.S. Inventory. 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 U.S. definitions of managed and unmanaged lands are 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 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. Managed land also includes legal protection of lands (e.g., wilderness, preserves, parks, etc.) for conservation purposes (i.e., meets societal objectives).[9]
- *Unmanaged Land:* All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to human intervention due to the remoteness of the locations, or lands with essentially no development interest or protection due to limited personal, commercial or social value. Though these lands may be influenced indirectly by human actions such as atmospheric deposition of chemical species produced in industry, they are not influenced by a direct human intervention.[10]

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 U.S. 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,[11] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[12] The definitions for

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[9] 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 is difficult, however, 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.

[10] There will be some areas that qualify as forest land or grassland according to the land use criteria, but are classified as unmanaged land due to the remoteness of their location.

[11] See <http://socrates.lv-hrc.nevada.edu/fia/ab/issues/pending/glossary/Glossary_5_30_06.pdf>.

[12] See <http://www.nrcs.usda.gov/technical/land/nri01/glossary.html>.

Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land:* A land-use category that includes land that is at least 10 percent stocked[13] by forest trees of any size, or land formerly having such tree cover, and not currently developed for a non-forest use. The minimum area for classification as Forest Land is one acre (0.40 ha). Roadside, stream-side, and shelterbelt strips of timber must be at least 120 feet (36.58 m) wide to qualify as Forest Land. Unimproved roads and trails, streams and other bodies of water, or natural clearings in forested areas are classified as Forest Land, if less than 120 feet (36.58 m) in width or one acre (0.40 ha) in size. Improved roads within Forest Land, however, are extracted from forest area estimates and included in Settlements. Grazed woodlands, fields reverting to forest, and pastures that are not actively maintained are included if the above qualifications are satisfied. Forest Land consists of three main subcategories: timberland, reserved forest land, and other forest land.[14] Forest Land also includes woodlands, which describes forest types consisting primarily of species that have their diameter measured at root collar, and for which there are no site index equations, nor stocking guides. These may include areas with degrees of stocking between 5 and 9.9 percent. The FIA regions with woodland areas are, however, considering new definitions that should result in all Forest Land meeting the minimum 10 percent stocking threshold.
- *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 alley cropping and windbreaks,[15] as well as lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[16]). 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, 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. Savannas, some wetlands and deserts, in addition to tundra are considered Grassland.[17] 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, 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 area estimates 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. 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 covered in other areas of the IPCC guidance and/or the inventory, including Cropland (e.g., rice cultivation), Grassland, and Forest Land (including drained or undrained 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;

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[13] The percentage stocked refers to the degree of occupancy of land by trees, measured either by basal area or number of trees by size and spacing or both, compared to a stocking standard.

[14] These subcategory definitions are fully described in the *Forest Land Remaining Forest Land* section.

[15] 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.

[16] 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.

[17] IPCC (2006) guidelines do not include provisions to separate desert and tundra as land categories.

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 settlement category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland) are also included in Settlements.

- *Other Land:* A land-use category that includes bare soil, rock, ice, non-settlement transportation corridors, and all land areas that do not fall into any of the other five land-use categories. It allows the total of identified land areas to match the managed national area.

Land Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land Use Data Sources

The three main data sources for land area and use data in the United States are the NRI, FIA, and the NLCD. For the Inventory, the NRI is the official source of data on all land uses on non-federal lands (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 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 U.S. 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 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. This Inventory incorporates data through 2003 from the NRI.

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory. 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 had been conducted periodically, with all plots in a state being measured at a frequency of every 5 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 5 years. See Annex 3.12 to see the specific survey data available by state. The most recent year of available data varies state by state (2002 through 2007).

Though NRI provides land-area data for both federal and non-federal lands, it only includes land-use data on non-federal lands, and FIA only records data for forest land.[18] Consequently, major gaps exist when the datasets are combined, such as federal grassland operated by the Bureau of Land Management (BLM), USDA, and National Park Service, as well as most of Alaska.[19] Consequently, the NLCD is used as a supplementary database to account for land use on federal lands that are not included in the NRI and FIA databases. The NLCD is a land-cover classification scheme, available for 1992 and 2001, that has been applied over the conterminous United States. For this analysis, the

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[18] 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.

[19] The 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 U.S. Territories.

NLCD Retrofit Land Cover Change Product was used in order to represent both land use and land-use change for federal lands. It is based primarily on Landsat Thematic Mapper imagery. The NLCD contains 21 categories of land cover information, which have been aggregated into the IPCC land-use categories, and the data are available at a spatial resolution of 30 meters. The federal land portion of the NLCD was extracted from the dataset using the federal land area boundary map from the National Atlas.[20] This map represents federal land boundaries in 2005, so as part of the analysis, the federal land area was adjusted annually based on the NRI federal land area estimates (i.e., land is periodically transferred between federal and non-federal ownership). Consequently, the portion of the land base categorized with NLCD data varied from year to year, corresponding to an increase or decrease in the federal land base. The 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.

Another step in the analysis is to address gaps, as well as overlaps, in the representation of the U.S. land base between the Agricultural Carbon Stock Inventory (*Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*) and Forest Land Carbon Stock Inventory (*Forest Land Remaining Forest Land* and *Land Converted to Forest Land*), which are based on the NRI and FIA databases, respectively. NRI and FIA have different criteria for classifying forest land, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Moreover, dependence exists between the Forest Land area and the amount of land designated as other land uses in both the NRI as well as the NLCD, such as the amount of Grassland, Cropland and Wetland, relative to the Forest Land area. This results in inconsistencies among the three databases for estimated Forest Land area, as well as for the area estimates for other land-use categories. FIA is the main database for forest statistics, and consequently, the NRI and NLCD were adjusted to achieve consistency with FIA estimates of Forest Land. The adjustments were made at a state scale, and it was assumed that the majority of the discrepancy in forest area was associated with an under- or over-prediction of grassland and wetland area in the NRI and NLCD due to differences in Forest Land definitions. Specifically, the Forest Land area for a given state according to the NRI and NLCD was adjusted to match the FIA estimates of Forest Land for non-federal and federal land, respectively. In a second step, corresponding increases or decreases were made in the area estimates of Grassland and Wetland from the NRI and NLCD, in order to balance the change in forest area, and therefore not change the overall amount of managed land within an individual state. The adjustments were 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 and vice versa).

As part of Quality Assurance/Quality Control (QA/QC), the land base derived from the NRI, FIA, and NLCD was compared to the U.S. Census Survey.[21] 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, which is critical for conducting emission inventories and is provided from the NRI and FIA surveys. Consequently, the U.S. Census Survey was not adopted as the official land-area estimate for the Inventory. Rather the NRI data were adopted given that this database provides full coverage of land area for the conterminous United States and Hawaii. Regardless, the total difference between the U.S. Census Survey and the data sources used in the Inventory is about 25 million hectares for the total land base of about 785 million hectares currently included in the Inventory, or a 3.1 percent difference. Much of this difference is associated with open waters in coastal regions and the Great Lakes. NRI does not include as much of the area of open waters in these regions as the U.S. Census Survey.

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[20] See <http://nationalatlas.gov/atlasftp.html?openChapters=chpbound#chpbound>.

[21] See <http://www.census.gov/geo/www/tiger>.

Approach for Combining Data Sources

The managed land base in the United States has been classified into the six IPCC land-use categories using definitions[22] developed to meet national circumstances, while adhering to IPCC (2006). In practice, the land was initially classified into a variety of land-use categories using the NRI, FIA and NLCD, and then aggregated into the thirty-six broad land use and land use change categories identified in IPCC (2006). Details on the approach used to combine data sources for each land use are described below as are the gaps that will be reconciled as part of ongoing planned improvements:

- *Forest Land:* Both non-federal and federal forest lands on both the continental 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. Interior Alaska is not currently surveyed by FIA, but NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports. Forest Land in U.S. territories are currently excluded from the analysis, but FIA surveys are currently being conducted on U.S. territories and will become available in the future. NRI is being used in the current report to provide Forest Land areas on non-federal lands in Hawaii. Federal forest land in Hawaii is currently excluded, but 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 C stocks and fluxes on Cropland. Cropland in U.S. territories are excluded from both NRI data collection and the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.
- *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 C stocks and fluxes on Grassland. U.S. territories are excluded from both NRI data collection and the current release of the NLCD product. Grassland on federal Bureau of Land Management lands, Department of Defense lands, National Parks and within USFS lands are covered by the NLCD, with the exception of federal grasslands in Hawaii, which will be added as a planned improvement in the future. In addition, federal and non-federal grasslands in Alaska are currently excluded from the analysis, but NLCD has a new product for Alaska that will be incorporated into the assessment for future reports.
- *Wetlands:* NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while federal wetlands are covered by the NLCD, with the exception of federal lands in Hawaii, which will be added as a planned improvement in the future. Alaska and U.S. territories are excluded. This currently includes both managed and unmanaged wetlands as no database has yet been applied to make this distinction. See Planned Improvements for details.
- *Settlements:* The 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 nonforest by FIA if it is located within an urban area. Settlements on federal lands are covered by NLCD, with the exception of federal lands in Hawaii, which will be added as a planned improvement in the future. Settlements in U.S. territories are currently excluded from NRI and NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.
- *Other Land:* Any land not falling into the other five land categories and, therefore, categorized as Other Land is classified using the NRI for non-federal areas in the 49 states (excluding Alaska) and NLCD for the federal lands, with the exception of federal lands in Hawaii, which will be added as a planned improvement in the future. Other land in U.S. territories is excluded from the NLCD. NLCD has a new product for Alaska that will be incorporated into the assessment as a planned improvement for future reports.

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[22] Definitions are provided in the previous section.

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 initiated by distinguishing between managed and unmanaged lands. The managed lands are then assigned, 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 grass 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 that are used for rice production are considered Croplands. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and Other Land complete the list.

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 single 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 to produce a crop, such as rice. In either case, emissions from Wetlands are included in the Inventory if human interventions are influencing emissions from Wetlands, in accordance with the guidance provided in IPCC (2006).

Recalculations/Revisions

Three major revisions were made in the current Inventory for land representation.

- First, land uses were further disaggregated by land use and land-use change categories as recommended by IPCC (2006), which was possible with the new NLCD Retrofit Product in combination with the NRI data. This change provides additional information on land-use trends in the United States, and is expected to improve estimation of greenhouse gas emissions and transparency of the report.
- Second, rural transportation corridors were re-classified as Settlements, instead of including these areas in the Other Land category. Transportation corridors are managed in a manner more similar to land use practices typically associated with Settlements, and therefore more aligned with this land-use category.
- Finally, the NRI was adopted as the official land area estimate for the U.S. Inventory. This change led to a decline in the managed land base for the United States because the NRI does not include some of the open water areas in the Great Lakes and ocean coastal regions. Currently, there is no estimation of greenhouse gas emissions associated with open waters of these regions from the perspective of land use, and so this change has no consequences on the estimates of anthropogenic greenhouse gas emissions for the Inventory.

Planned Improvements

Area data by land-use category are not estimated for major portions of Alaska, federal lands in Hawaii, or any of the U.S. territories. A key planned improvement is to incorporate land-use data from these areas in the National Greenhouse Gas Emissions Inventory. For Alaska, a new NLCD 2001 data product will be used to cover those land areas presently omitted. 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. Data sources will also be evaluated for representing land use on federal lands in Hawaii and federal and non-federal lands in U.S. territories.

Additional work will be done to reconcile differences in Forest Land estimates between the NRI and FIA, evaluating the assumption that the majority of discrepancies in Forest Land areas are associated with an over- or under-estimation of Grassland and Wetland area. In some regions of the United States, a discrepancy in Forest Land areas between NRI and FIA may be associated with an over- or under-prediction of other land uses.

There are also other databases that may need to be reconciled with the NRI and NLCD datasets, particularly for Settlements and Wetlands. Urban area estimates, used to produce C stock and flux estimates from urban trees, are currently based on population data (1990 and 2000 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. For Wetlands, the Army Corps of Engineers National Inventory of Dams (NID) (ACE 2005) and the U.S. Fish and Wildlife Service National Wetlands Inventory (NWI)[23] databases are being evaluated and will be compared against the NRI and NLCD. The NID and NWI may be used to refine wetland area estimates for the U.S. Land Representation assessment, including disaggregation of managed and unmanaged wetlands.

7.2. Forest Land Remaining Forest Land

Changes in Forest Carbon Stocks (IPCC Source Category 5A1)

For estimating C stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2003):

- 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 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 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 aboveground pools.

In addition, there are two harvested wood pools necessary for estimating C flux:

- Harvested wood products in use.
- Harvested wood products in solid waste disposal sites (SWDS).

Carbon is continuously cycled among these storage pools and between forest ecosystems and the atmosphere as a result of biological processes in forests (e.g., photosynthesis, respiration, growth, mortality, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, clearing, 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 or transferred to the soil 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 C to the atmosphere. Instead, harvesting transfers C to a "product pool." Once in a product pool, the C is emitted over time as CO_2 when the wood product combusts or decays. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately. 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.

This section quantifies the net changes in C stocks in the five forest C pools and two harvested wood pools. The

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[23] See <http://www.fws.gov/nwi/>.

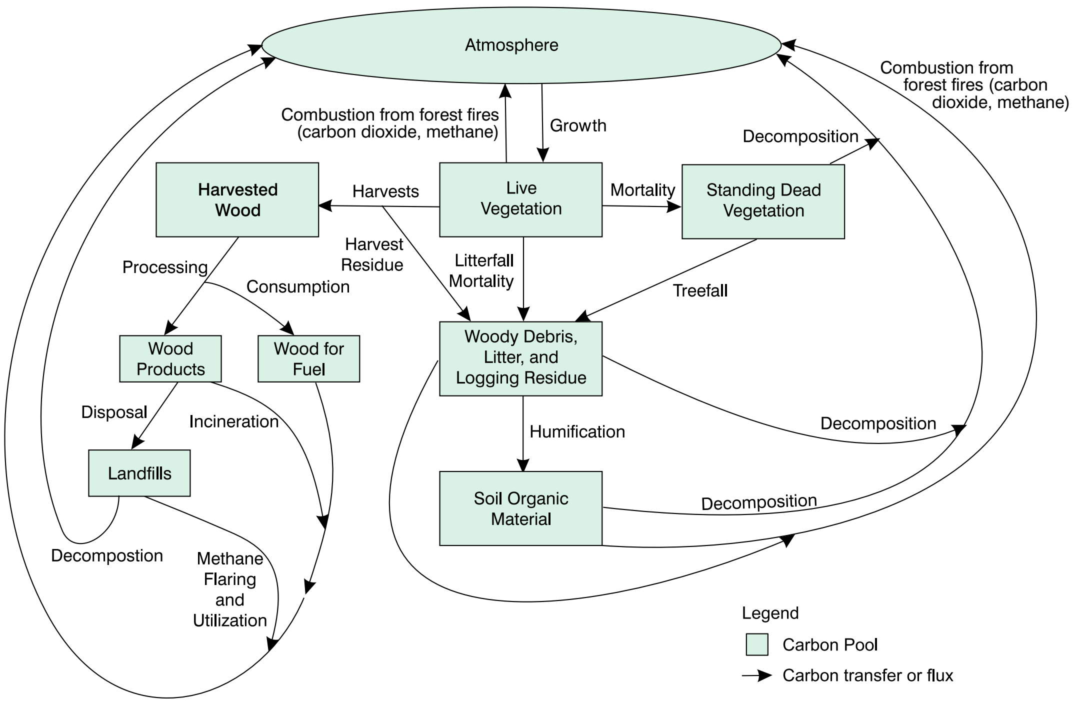
net change in stocks for each pool is estimated, and then the changes in stocks are summed over all pools to estimate total net flux. The focus on C implies that all C-based greenhouse gases are included, and the focus on stock change suggests that specific ecosystem fluxes do not need to be separately itemized in this report. Disturbances from forest fires and pest outbreaks are implicitly included in the net changes. For instance, an inventory conducted after fire counts only trees left. The change between inventories thus accounts for the C changes due to fires; however, it may not be possible to attribute the changes to the disturbance specifically. The IPCC (2003) recommends reporting C stocks according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. Currently, consistent datasets are not available for the entire United States to allow results to be partitioned in this way. Instead, net changes in all forest-related land, including non-forest land converted to forest and forests converted to non-forest are reported here.

Forest C storage pools, and the flows between them via emissions, sequestration, and transfers, are shown in Figure 7-2. In the figure, boxes represent forest C storage pools and arrows represent flows between storage pools or between storage pools and the atmosphere. Note that the boxes are not identical to the storage pools identified in this chapter. The storage pools identified in this chapter have been altered in this graphic to better illustrate the processes that result in transfers of C from one pool to another, and emissions to the atmosphere as well as uptake from the atmosphere.

Approximately 33 percent (304 million hectares) of the U.S. land area is forested (Smith et al. 2008). The current forest inventory includes 250 million hectares in the conterminous 48 states (USDA Forest Service 2008a, 2008b) that are considered managed and are included in this Inventory. The additional forest lands are located in Alaska and Hawaii. This Inventory includes approximately 3.8 million hectares of Alaska forest, which are in the southeast and south central regions of Alaska and represent the majority of the state's managed forest land. Survey data are not yet available from Hawaii. While Hawaii and U.S. territories have relatively small areas of forest land and will probably not affect the overall C budget to a great degree, these areas will be included as sufficient data becomes available. Agroforestry systems are also not currently accounted for in the Inventory, since they are not explicitly inventoried by either of the two primary national natural resource inventory

Figure 7-2

Forest Sector Carbon Pools and Flows



Source: Heath et al. 2003

programs: the Forest Inventory and Analysis (FIA) program of the U.S. Department of Agriculture (USDA) Forest Service and the *National Resources Inventory* (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

Sixty-eight percent of U.S. forests (208 million hectares) are classified as timberland, meaning they meet minimum levels of productivity and are available for timber harvest. Nine percent of Alaska forests and 81 percent of forests in the conterminous United States are classified as timberlands. Of the remaining nontimberland forests, 30 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 66 million hectares are lower productivity forest lands (Smith et al. 2008). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than other forest lands.

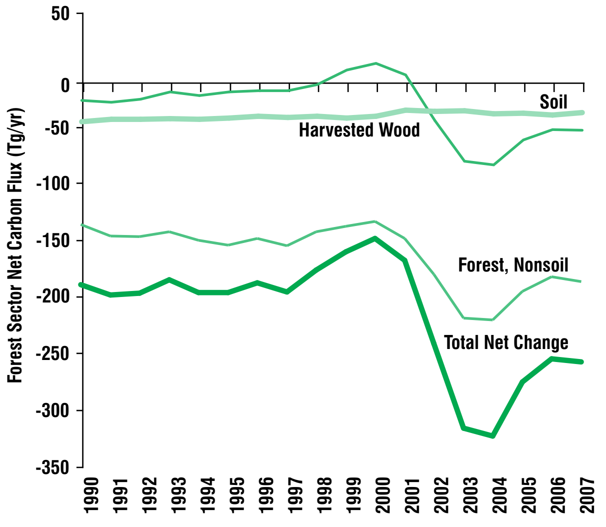
Forest land declined by approximately 10 million hectares over the period from the early 1960s to the late 1980s. Since then, forest area has increased by about 8 million hectares. Current trends in forest area represent average annual change of less than 0.2 percent. Given the low rate of change in U.S. forest land area, the major influences on the current net C flux from forest land are management activities and the ongoing impacts of previous land-use changes. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems. For example, intensified management of forests that leads to an increased rate of growth increases the eventual biomass density of the forest, thereby increasing the uptake of C.[24] Though harvesting forests removes much of the aboveground C, there is a positive growth to harvest ratio on U.S. timberlands (AF&PA 2001) . The reversion of cropland to forest land increases C storage in biomass, forest floor, and soils. The net effects of forest management and the effects of land-use change involving forest land are captured in the estimates of C stocks and fluxes presented in this chapter.

In the United States, improved forest management practices, the regeneration of previously cleared forest areas, as well as timber harvesting and use have resulted in net uptake (i.e., net sequestration) of C each year from 1990 through 2007. The rate of forest clearing begun in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still affect 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. forests 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 long-term storage pools rather than being released rapidly to the atmosphere (Skog and Nicholson 1998, Skog 2008). The size of these long-term C storage pools has increased during the last century.

Changes in C stocks in U.S. forests and harvested wood were estimated to account for net sequestration of 910.1 Tg CO_2 Eq. (248.2 Tg C) in 2007 (Table 7-6, Table 7-7, Figure 7-3 and Table 7-8). In addition to the net accumulation of C in harvested wood pools, sequestration is a reflection of net forest growth and increasing forest area over this

Figure 7-3

Estimates of Net Annual Changes in Carbon Stocks for Major Carbon Pools



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[24] 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 50 percent C by weight.

Table 7-6: Net Annual Changes in C Stocks (Tg CO_2/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2005	2006	2007
Forest	**(529.3)**	**(568.2)**	**(399.7)**	**(871.7)**	**(791.7)**	**(809.6)**
Aboveground Biomass	(321.5)	(390.9)	(352.1)	(469.4)	(442.7)	(452.4)
Belowground Biomass	(61.8)	(78.2)	(71.5)	(93.3)	(88.9)	(90.7)
Dead Wood	(15.4)	(27.3)	(18.2)	(39.4)	(35.6)	(36.8)
Litter	(67.8)	(37.2)	(14.8)	(79.6)	(68.7)	(70.8)
Soil Organic Carbon	(62.8)	(34.6)	56.9	(190.1)	(155.9)	(158.9)
Harvested Wood	**(131.8)**	**(118.4)**	**(112.9)**	**(103.9)**	**(108.6)**	**(100.4)**
Products in use	(64.8)	(55.2)	(47.0)	(44.1)	(45.2)	(36.9)
SWDS	(67.0)	(63.2)	(65.9)	(59.8)	(63.3)	(63.5)
Total Net Flux	**(661.1)**	**(686.6)**	**(512.6)**	**(975.7)**	**(900.3)**	**(910.1)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, western Texas 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 7-7: Net Annual Changes in C Stocks (Tg C/yr) in Forest and Harvested Wood Pools

Carbon Pool	1990	1995	2000	2005	2006	2007
Forest	**(144.3)**	**(155.0)**	**(109.0)**	**(237.7)**	**(215.9)**	**(220.8)**
Aboveground Biomass	(87.7)	(106.6)	(96.0)	(128.0)	(120.7)	(123.4)
Belowground Biomass	(16.8)	(21.3)	(19.5)	(25.5)	(24.2)	(24.7)
Dead Wood	(4.2)	(7.4)	(5.0)	(10.7)	(9.7)	(10.0)
Litter	(18.5)	(10.1)	(4.0)	(21.7)	(18.7)	(19.3)
Soil Organic Carbon	(17.1)	(9.4)	15.5	(51.9)	(42.5)	(43.3)
Harvested Wood	**(35.9)**	**(32.3)**	**(30.8)**	**(28.3)**	**(29.6)**	**(27.4)**
Products in use	(17.7)	(15.1)	(12.8)	(12.0)	(12.3)	(10.1)
SWDS	(18.3)	(17.2)	(18.0)	(16.3)	(17.3)	(17.3)
Total Net Flux	**(180.3)**	**(187.2)**	**(139.8)**	**(266.1)**	**(245.5)**	**(248.2)**

Note: Forest C stocks do not include forest stocks in U.S. territories, Hawaii, a large portion of Alaska, western Texas 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.

period. Overall, average C in forest ecosystem biomass (aboveground and belowground) increased from 70 to 76 Mg C/ha between 1990 and 2008 (see Annex 3-12 for average C densities by specific regions and forest types). Continuous, regular annual surveys are not available over the period for each state; therefore, estimates for non-survey years were derived by interpolation between known data points. Survey years vary from state to state, and national estimates are a composite of individual state surveys. Therefore, changes in sequestration over the interval 1990 to 2007 are the result of the sequences of new inventories for each state. C in forest ecosystem biomass had the greatest effect on total change through increases in C density and total forest land. Management practices that increase C stocks on forest land, as well as afforestation and reforestation efforts, influence the trends of increased C densities in forests and increased forest land in the United States.

Stock estimates for forest and harvested wood C storage pools are presented in Table 7-8. Together, the aboveground live and forest soil pools account for a large proportion of total forest C stocks. C stocks in all non-soil pools increased over time. Therefore, C sequestration was greater than C emissions from forests, as discussed above. Figure 7-4 shows county-average C densities for live trees on forest land, including both above- and belowground biomass.

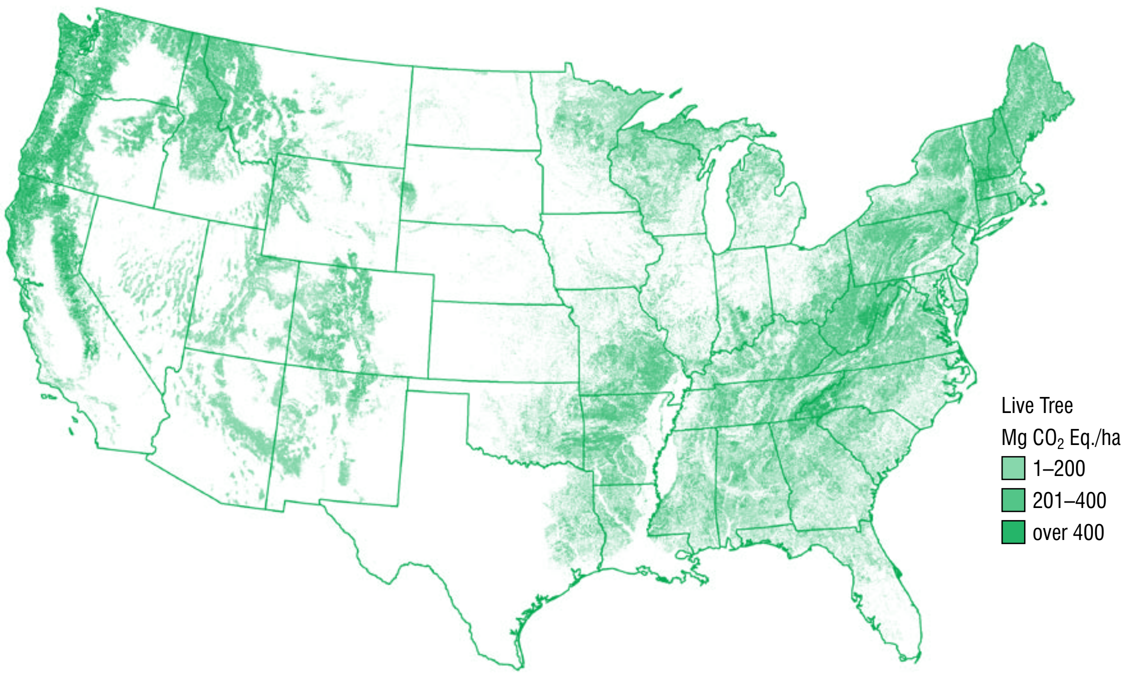
Table 7-8: Forest Area (1000 ha) and C Stocks (Tg C) in Forest and Harvested Wood Pools

	1990	1995	2000	2005	2006	2007	2008
Forest Area (1000 ha)	**245,697**	**249,240**	**251,732**	**255,358**	**256,227**	**257,001**	**257,787**
Carbon Pools (Tg C) Forest	**40,011**	**40,762**	**41,475**	**42,488**	**42,726**	**42,942**	**43,163**
Aboveground Biomass	14,378	14,845	15,365	15,974	16,102	16,222	16,346
Belowground Biomass	2,860	2,950	3,055	3,177	3,203	3,227	3,252
Dead Wood	2,541	2,567	2,597	2,640	2,651	2,660	2,670
Litter	4,558	4,651	4,690	4,772	4,794	4,813	4,832
Soil Organic C	15,675	15,748	15,767	15,925	15,977	16,019	16,063
Harvested Wood	**1,783**	**1,963**	**2,124**	**2,271**	**2,296**	**2,325**	**2,353**
Products in Use	1,193	1,280	1,355	1,413	1,423	1,436	1,446
SWDS	590	683	769	857	873	890	907
Total C Stock	**41,794**	**42,724**	**43,599**	**44,759**	**45,023**	**45,267**	**45,515**

Note: Forest area estimates include portions of Alaska. Forest C stocks do not include forest stocks in U.S. territories, Hawaii, western Texas, a large portion of Alaska, or trees on non-forest land (e.g., urban trees, agroforestry systems). Wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Forest area estimates are based on interpolation and extrapolation of inventory data as described in Smith et al. (2007, in press) and in Annex 3.12. 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 2006 requires estimates of C stocks for 2006 and 2007.

Figure 7-4

Average C Density in the Forest Tree Pool in the Conterminous United States, 2008



Note: This graphic shows county-average carbon densities for live trees on forestland, including both above- and belowground biomass. These data are based on the most recent forest inventory survey in each state. (See Table A-3 for the most recent inventory year for each state or substate.)

Box 7-1: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly accounts for emissions 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 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. forestland already account for CO_2 emissions from forest fires occurring in the lower 48 states as well as in the proportion of Alaska's managed forest land captured in this Inventory. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these estimates are being highlighted here, using the full extent of available data. Non-CO_2 greenhouse gas emissions from forest fires are also quantified in a separate section below.

Table 7-9: Estimates of CO_2 (Tg/yr) Emissions for the Lower 48 States and Alaska[a]

Year	CO_2 Emitted from Wildfires in Lower 48 States (Tg/yr)	CO_2 Emitted from Prescribed Fires in Lower 48 States (Tg/yr)	CO_2 Emitted from Wildfires in Alaska (Tg/yr)	Total CO_2 Emitted (Tg/yr)
1990	38.6	7.8	+	46.4
1995	53.6	8.6	+	62.3
2000	207.0	2.0	+	209.0
2005	120.9	22.9	+	143.8
2006	289.5	27.0	+	316.6
2007	262.3	31.4	+	293.7

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Note that 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.

The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate CO_2 emissions from forest fires. CO_2 emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2007 were estimated to be 293.7 Tg CO_2/yr. This amount is masked in the estimate of net annual forest carbon stock change for 2007, however, because this net estimate accounts for the amount sequestered minus any emissions.

Methodology and Data Sources

The methodology described herein is consistent with IPCC (2003, 2006) and IPCC/UNEP/OECD/IEA (1997). Forest ecosystem C stocks and net annual C stock change are determined according to stock-difference methods, which involve applying C estimation factors to forest inventory data and interpolating between successive inventory-based estimates of C stocks. Harvested wood C estimates are 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 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 3.12 for details and additional information related to the methods and data.

Forest Ecosystem Carbon from Forest Inventory

Forest ecosystem stock and flux estimates are based on the stock-difference method and calculations for all estimates are in units of C. Separate estimates are made for the five IPCC C storage pools described above. All estimates are based on data collected from the extensive array of permanent forest inventory plots in the United States as well as models employed to fill gaps in field data. Carbon conversion factors are applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. A combination of tiers as outlined by Eggleston et al. (2006) is used. The Tier 3 biomass C values are from forest inventory tree-level data. The Tier 2 dead organic and soil C pools are based on empirical or process models from the inventory data. All carbon conversion factors are specific to regions or individual states within the United States, which are further classified according to characteristic forest types within each region.

The first step in developing forest ecosystem estimates is to identify useful inventory data and resolve any inconsistencies among datasets. Forest inventory data were obtained from the USDA Forest Service FIA program (Frayer and Furnival 1999, USDA Forest Service 2008a). Inventories include data collected on permanent inventory plots on forest lands[25] and are organized as a number of separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Some of the more recent annual inventories reported for some states include "moving averages" which means that a portion—but not all—of the previous year's inventory is updated each year (USDA Forest Service 2008d). Forest C calculations are organized according to these state surveys, and the frequency of surveys varies by state. All available datasets are identified for each state starting with pre-1990 data where possible and including all surveys since then. Since C stock change is based on differences between successive surveys within each state, accurate estimates of net C flux thus depend on consistent representation of forest land between these successive inventories. In order to achieve this consistency from 1990 to the present, state-level data are sometimes subdivided in cases where the sum of sub-state inventories produces the best whole-state represention of C change as discussed in Smith et al. (2007).

The principal FIA datasets employed are freely available for download at USDA Forest Service (2008b) as the Forest Inventory and Analysis Database (FIADB) Version 3.0. However, to achieve consistent representation (spatial and temporal), two other general sources of past FIA data are included as necessary. First, older FIA plot- and tree-level data—not in the current FIADB format—are used if available. Second, Resources Planning Act Assessment (RPA) databases, which are periodic, plot-level-only summaries of state inventories, are used mostly to provide the data at or before 1990. See USDA Forest Service (2008a) for information on current and older data as well as additional FIA Program features. A detailed list of the specific inventory data used in this Inventory is in Annex 3.12.

Forest C stocks are estimated from inventory data by a collection of conversion factors and models referred to as FORCARB2 (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004a), which have been formalized in an FIADB-to-carbon calculator (Smith et al. 2007, in press). The conversion factors and model coefficients are categorized by region and forest type, and forest C stock estimates are calculated from application of these factors at the scale of FIA inventory plots. The results are estimates of C density (Mg C per hectare) for six forest ecosystem pools: live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic matter. The six carbon pools used in the FIADB-to-carbon calculator are aggregated to the 5 carbon pools defined by IPCC (2006): aboveground biomass, belowground biomass, dead wood, litter and soil organic matter. All non-soil pools except forest floor are separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass, and standing dead trees and down dead wood are pooled as dead wood, in accordance with IPCC (2006).

Once plot-level C stocks are calculated as C densities on *Forest Land Remaining Forest Land* for the five IPCC (2006) reporting pools, the stocks are expanded to population estimates according to methods appropriate to the respective inventory data (for example, see USDA Forest Service (2008d)). These expanded C stock estimates are summed to state or sub-state total C stocks. Annualized estimates of C stocks are developed by using available FIA inventory data and interpolating or extrapolating to assign a C stock to each year in the 1990 through 2008 time series. Flux, or net annual stock change, is estimated by calculating the difference between two successive years and applying the appropriate sign convention; net increases in ecosystem C are identified as negative flux. By convention, inventories are assigned to represent stocks as of January 1 of the inventory year; an estimate of flux for 1996 requires estimates of C stocks for 1996 and 1997, for example. For this Inventory, 2008 stock and 2007 flux are based on extrapolation of the average of the most recent three years of interpolated flux in the time series. Additional discussion of the use of FIA inventory data and the C conversion process is in Annex 3.12.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for full-tree and aboveground-only biomass in order to estimate the belowground component. If inventory plots include data on individual trees, tree C is based on Jenkins et al. (2003) and is a function of species and diameter. Some inventory data do not provide measurements of individual trees; tree C in these plots is estimated from plot-level volume of merchantable

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[25] Forest land in the United States includes land that is at least 10 percent stocked with trees of any size. Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood.

wood, or growing-stock volume, of live trees, which is calculated from updates of Smith et al. (2003). These biomass conversion and expansion factors (BCEFs) are applied to about 5 percent of the inventory records, all of which are pre-1998 data. Some inventory data, particularly some of the older datasets, may not include sufficient information to calculate tree C because of incomplete or missing tree or volume data; C estimates for these plots are based on averages from similar, but more complete, inventory data. This applies to an additional 3 percent of inventory records, which represent older (pre-1998) non-timberlands.

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 d.b.h. In this inventory, it is assumed that 10 percent of total understory C mass is belowground. Estimates of C density are based on information in Birdsey (1996). Understory frequently represents over 1 percent of C in biomass, but its contribution rarely exceeds 2 percent of the total.

Carbon in Dead Organic Matter

Dead organic matter is initially calculated as three separate pools with C stocks modeled from inventory data. Estimates are specific to regions and forest types within each region, and stratification of forest land for dead organic matter calculations is identical to that used for biomass through the state and sub-state use of FIA data as discussed above. The two components of dead wood—standing dead trees and down dead wood—are estimated separately. The standing dead tree C pools include aboveground and belowground (coarse root) mass and include trees of at least 2.54 cm d.b.h. Calculations are BCEF-like factors based on updates of Smith et al. (2003). Down 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. Down dead wood includes stumps and roots of harvested trees. Ratios of down dead wood to live tree are used to estimate this quantity. 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. Estimates are based on equations of Smith and Heath (2002).

Carbon in Forest Soil

Soil organic C includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC are based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. SOC determination is based on the general approach described by Amichev and Galbraith (2004). Links to FIA inventory data were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map. This method produced mean SOC densities stratified by region and forest type group. It did not provide separate estimates for mineral or organic soils but instead weighted their contribution to the overall average based on the relative amount of each within forest land. Thus, forest SOC is a function of species and location, and net change also depends on these two factors as total forest area changes. In this respect, SOC provides a country-specific reference stock for 1990-present, but it does not reflect effects of past land use.

Harvested Wood Carbon

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP C. IPCC (2006) provides methods that allow Parties to report 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 3.12 for more details about each approach). The United States uses the production accounting approach to report HWP Contribution. Under the production approach, C in exported wood is estimated as if it remains in the United States, and C in imported wood is not included in inventory estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.12). Annual estimates of change are 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 solid waste disposal sites (SWDS).

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 are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are 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). Estimates for disposal of products reflect the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that are in sanitary landfills versus dumps.

There are 5 annual HWP variables that are used in varying combinations to estimate HWP Contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yields the estimate for HWP Contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on current flux for forest ecosystems as well as carbon in harvested wood products through Monte Carlo simulation of the methods described above and probabilistic sampling of carbon conversion factors and inventory data. See Annex 3.12 for additional information. The 2007 flux estimate for forest C stocks is estimated to be between -736 and -1083 Tg CO_2 Eq. at a 95 percent confidence level. (See Table 7-10). This includes a range of -638 to -981 Tg CO_2 Eq. in forest ecosystems and -76 to -127 Tg CO_2 Eq. for HWP. The relatively smaller range of uncertainty, in terms of percentage, for the total relative to the two separate parts in because the total is based on summing the two independent uncertain parts.

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 main purpose of the FIA program has been to estimate areas, volume of growing stock, and timber products output and utilization factors. 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,

Table 7-10: Tier 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem	CO_2	(809.6)	(980.9)	(637.5)	-21%	+21%
Harvested Wood Products	CO_2	(100.4)	(127.0)	(76.2)	-26%	+24%
Total Forest	**CO_2**	**(910.1)**	**(1,083.1)**	**(735.6)**	**-19%**	**19%**

[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.

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 2008c).

Many key calculations for estimating current forest C stocks based on FIA data are based on coefficients from the FORCARB2 model (see additional discussion in the Methodology section above and in Annex 3.12). The model has been used for many years to produce national assessments of forest C stocks and stock changes. General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the derived C datasets, which include inventory variables such as areas and volumes, were compared with standard inventory summaries such as Resources Planning Act (RPA) Forest Resource Tables or selected population estimates generated from the FIA Database (FIADB), which are available at an FIA Internet site (USDA Forest Service 2008d). 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 from original units to C units 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 verified by two independent criteria. The first criteria 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 criteria 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 criteria is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards each year over the period 1990 to 2000. 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 reduces uncertainty in estimates of annual change in C in products made from wood harvested in the United States.

Recalculations Discussion

The basic models used to estimate forest ecosystem and HWP C stocks and change are largely unchanged from the previous Inventory (Smith et al. 2007, Skog 2008). Most of the estimates for 1990–present are relatively similar to the values previously reported (EPA 2008). However, changes in underlying FIA data have driven some changes in estimates across the time series. Most states have added new inventory data or modified some of the information in previously existing surveys and the FIADB format changed to version 3.0 (USDA Forest Service 2008b). The change to FIADB 3.0 resulted in three broad changes to the carbon calculation methods of Smith et al. (2007), affecting: (1) expansion of plot-level carbon to total carbon stocks; (2) the more complete use of the moving averages; and (3) the method of extrapolating stock and stock change, which is related to the use of the moving averages. See Smith et al. (2007, in press) for further discussion. The plot-level carbon conversion process is essentially unchanged. However, the process for expanding carbon to the totals used for determining net stock change is modified somewhat from Smith et al. (2007) according to methods described in the current FIADB user's guide (USDA Forest Service 2008d, Smith et al. in press).

The increasing number of annual inventory reports from moving averages (USDA Forest Service 2008b), especially in the eastern U.S., are incorporated into this year's Inventory (see Annex 3.12). The newly available annual inventory data necessitated the second broad update to the carbon calculator, which was to incorporate the use of all of these annual data summaries. Their use was minimized in previous forest carbon inventories (Smith et al. 2007, in press). Moving averages have the potential for greater inter-annual variability in stocks for some states, which in turn can have an even greater effect on carbon change because of the greater sensitivity in change (Smith et al. 2007). That is, a very small change in stock can have a tremendous effect on stock change, which is based on a small difference between two very large values. The use of the moving averages and the related sensitivity of stock change led to the third general change in the calculator, which is the method of extrapolation applied. Extrapolated values are based on short-term trends rather than being subject to a single year.

Most of these changes in data sources or methodology had only minor effects on estimates for 1990–present. A notable exception is the spike in net annual changes in C stocks for forest ecosystem C after 2000; this spike occurs in all five forest ecosystem pools to different degrees. Carbon change estimates generated for 2002 through 2006 are notably greater than the corresponding values from the previous Inventory. At the same time, the three previous years (1999, 2000, and 2001) show a slight decrease relative to values reported in the 1990–2006 Inventory. This combined effect is largely associated with forest areas reported by surveys over that interval and is a product of the interpolated stock differences from the FIADB. Comparing the relative rates of change in area versus overall C density for all forest carbon pools for 1990–2007 illustrates that the rate of change for carbon density is relatively steady, but the rate of change for area fluctuates considerably. Extrapolated portions of the 1990–present estimates are subject to change as new data become available and they generally include greater uncertainty. However, most of the increased carbon sequestration over 2000–2003 is based on interpolation between stocks because only 6 percent of the carbon change reported for 2003 is based on extrapolated values.

The uncertainty analysis for forest ecosystem carbon stock change has been revised. It is now possible to estimate sampling errors associated with each of the specific carbon pools reported here; this has been incorporated into the current uncertainty analysis (see Annex 3.12).

Planned Improvements

The ongoing annual surveys by the FIA Program will improve precision of forest C estimates as new state surveys become available (USDA Forest Service 2008a). The annual surveys will eventually include all states. To date, four states are not yet reporting any data from the annualized sampling design of FIA: Hawaii, Oklahoma, New Mexico, and Wyoming. Estimates for these states are currently based on older, periodic data. Hawaii and U.S. territories will also be included when appropriate forest C data are available. In addition, the more intensive sampling of down dead wood, litter, and soil organic C on some of the permanent FIA plots continues and will substantially improve resolution of C pools at the plot level for all U.S. forest land when this information becomes available. Improved resolution, incorporating more of Alaska's forests, and using annualized sampling data as it becomes available for those states currently not reporting are planned for future reporting.

As more information becomes available about historical land use, the ongoing effects of changes in land use and forest management will be better accounted for in estimates of soil C (Birdsey and Lewis 2003, Woodbury et al. 2006, Woodbury et al. 2007). Currently, soil C estimates are based on the assumption that soil C density depends only on broad forest type group, not on land-use history, but long-term residual effects on soil and forest floor C stocks are likely after land-use change. Estimates of such effects depend on identifying past land use changes associated with forest lands.

Similarly, agroforestry practices, such as windbreaks or riparian forest buffers along waterways, are not currently accounted for in the Inventory. In order to properly account for the C stocks and fluxes associated with agroforestry, research will be needed that provides the basis and tools for including these plantings in a nation-wide inventory, as well as the means for entity-level reporting.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using the default IPCC (2003) methodology and default IPCC (2006) combustion factor for wildfires. Emissions from this source in 2007 were estimated to be 29.0 Tg CO_2 Eq. of CH_4 and 2.9 Tg CO_2 Eq. of N_2O, as shown in Table 7-11 and Table 7-12. The estimates of non-CO_2 emissions from forest fires account for wildfires in the lower 48 states and Alaska as well as prescribed fires in the lower 48 states.

Table 7-11: Estimated Non-CO_2 Emissions from Forest Fires (Tg CO_2 Eq.) for U.S. Forests[a]

Gas	1990	1995	2000	2005	2006	2007
CH_4	4.6	6.1	20.6	14.2	31.3	29.0
N_2O	0.5	0.6	2.1	1.4	3.2	2.9
Total	**5.1**	**6.8**	**22.7**	**15.6**	**34.4**	**31.9**

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Table 7-12: Estimated Non-CO_2 Emissions from Forest Fires (Gg) for U.S. Forests[a]

Gas	1990	1995	2000	2005	2006	2007
CH_4	218	293	983	676	1,489	1,381
N_2O	2	2	7	5	10	9

[a] Calculated based on C emission estimates in *Changes in Forest Carbon Stocks* and default factors in IPCC (2003, 2006).

Methodology

The IPCC (2003) Tier 2 default methodology was used to calculate non-CO_2 emissions from forest fires. Estimates for CH_4 emissions were calculated by multiplying the total estimated C emitted (Table 7-13) from forest burned by gas-specific emissions ratios and conversion factors. N_2O emissions were calculated in the same manner, but were also multiplied by an N-C ratio of 0.01 as recommended by IPCC (2003). The equations used were:

$$CH_4 \text{ Emissions} = (\text{C released}) \times (\text{emission ratio}) \times 16/12$$

$$N_2O \text{ Emissions} = (\text{C released}) \times (\text{N/C ratio}) \times (\text{emission ratio}) \times 44/28$$

Estimates for C emitted from forest fires are the same estimates used to generate estimates of CO_2 emissions from forest fires, presented earlier in Box 7-1. Estimates for C emitted include emissions from wildfires in both Alaska and the lower 48 states as well as emissions from prescribed fires in the lower 48 states only (based on expert judgment that prescribed fires only occur in the lower 48 states) (Smith 2008a). The IPCC (2006) default combustion factor of 0.45 for "all 'other' temperate forests" was applied in estimating C emitted from both wildfires and prescribed fires. See the explanation in Annex 3.12 for more details on the methodology used to estimate C emitted from forest fires.

Table 7-13: Estimated Carbon Released from Forest Fires for U.S. Forests

Year	C Emitted (Tg/yr)
1990	13.6
1995	18.3
2000	61.4
2005	42.3
2006	93.0
2007	86.3

Uncertainty

Non-CO_2 gases emitted from forest fires depend on several variables, including: forest area for Alaska and the lower 48 states; average carbon densities for wildfires in Alaska, wildfires in the lower 48, and prescribed fires in the lower 48; emission ratios; and combustion factor values (proportion of biomass consumed by fire). To quantify the uncertainties for emissions from forest fires, a Monte Carlo (Tier 2) uncertainty analysis was performed using information about the uncertainty surrounding each of these variables. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-14.

Table 7-14: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	29.0	7.7	73.9	-73%	+155%
Non-CO_2 Emissions from Forest Fires	N_2O	2.9	0.8	7.4	-73%	+152%

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. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

Based on new data from the FIA National Program, average carbon density for Alaska was updated from 331 Mg/ha to 179 Mg/ha and for the lower 48 states from 89 Mg/ha to 91 Mg/ha. The previous value of 331 Mg/ha for Alaska was from a much smaller subset of Alaskan forest. The updated density values correspond directly to the forest land that the U.S. Forest Service uses to report carbon. Emissions from prescribed fires were included in the totals this year. Reported area burned for prescribed fires was taken from the National Interagency Fire Center and an average carbon density value of 30 Mg/ha was used based on expert judgment within the U.S. Forest Service. The IPCC (2006) default combustion factor for “all ‘other’ temperate forests” of 0.45 was used in place of the 0.40 factor previously used. Data for land area under wildland fire protection for the year 2006 was obtained from the National Association of State Foresters State Forestry Statistics 2006 Report. This affected emission estimates across the time series. See explanation in Annex 3.12 for more details on the methodology used to estimate land area under wildland fire protection for the time series. Based on expert judgment, new uncertainty parameters were applied, including updated uncertainty percentages and distributions surrounding the variables used in estimating emissions. These changes resulted in a wider uncertainty range relative to the previous Inventory.

Planned Improvements

The default combustion factor of 0.45 from IPCC (2006) was applied in estimating C emitted from both wildfires and prescribed fires. Additional research into the availability of a combustion factor specific to prescribed fires will be conducted.

Direct N_2O Fluxes from Forest Soils (IPCC Source Category 5A1)

Of the synthetic 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 cropped 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 approximately 20 years later). Thus, although the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, average annual applications, inferred by dividing all forest land that may undergo N fertilization at some point during its growing cycle by the amount of N fertilizer added to these forests in a given year, is quite low. N_2O emissions from forest soils are estimated to have increased by a multiple of 5.7 from 1990 to 2007. The trend toward increasing N_2O emissions is a result of an increase in the area of N fertilized pine plantations in the southeastern United States. Total forest soil N_2O emissions are summarized in Table 7-15.

Table 7-15: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	0.0	0.2
1995	0.1	0.4
2000	0.3	1.1
2005	0.3	1.0
2006	0.3	1.0
2007	0.3	1.0

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Forest Land Remaining Forest Land* and from *Land Converted to Forest Land*.

Methodology

The IPCC Tier 1 approach was used to estimate N_2O 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 were for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. It was assumed that southeastern pine plantations represent the vast majority of fertilized forests in the United States. Therefore, estimates of direct N_2O emissions from fertilizer applications to forests were based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh 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 was multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Data for areas of forests receiving fertilizer outside the southeastern United States were not available, so N additions to non-southeastern forests are not included here. Area data for pine plantations receiving fertilizer in the Southeast were not available for 2005, 2006 and 2007, so data from 2004 were used for these years. The N applied to forests was multiplied by the IPCC (2006) default emission factor of 1 percent to estimate direct N_2O emissions. The volatilization and leaching/runoff fractions, calculated according to the IPCC default factors of 10 percent and 30 percent, respectively, were included with all sources of indirect emissions in the Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology and only accounts for variations 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 the Agricultural Soil Management and *Settlements Remaining Settlements* sections.

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates were assigned a default level[26] of uncertainty at ±50 percent, and area receiving fertilizer was assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) provided estimates for the uncertainty associated with the direct N_2O emission factor for synthetic N fertilizer application to soils. Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2007 emissions estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-16. N_2O fluxes from soils were estimated to be between 0.1 and 1.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the 2007 emission estimate of 0.3 Tg CO_2 Eq.

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[26] Uncertainty is unknown for the fertilization rates so a conservative value of ±50% was used in the analysis.

Table 7-16: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Land Remaining Forest Land: N_2O Fluxes from Soils	N_2O	0.3	0.1	1.0	-59%	+211%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Recalculations Discussion

Number of acres fertilized and fertilizer application rate data for plantations in the southeastern United States receiving N fertilizer were updated based on Albaugh et al. (2007) from the previous Inventory. This resulted in a small decrease (less than 10 percent on average) in emissions compared to the previous Inventory.

Planned Improvements

State-level area data will be acquired for southeastern pine plantations receiving fertilizer to estimate soil N_2O emission by state and provide information about regional variation in emission patterns.

7.3. Land Converted to Forest Land (IPCC Source Category 5A2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to forest each year, just as forest land is converted to other uses. However, the magnitude of these changes is not currently known. Given the paucity of available land-use information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Forest Land* from fluxes on *Forest Land Remaining Forest Land* at this time.

7.4. Cropland Remaining Cropland (IPCC Source Category 5B1)

Mineral and Organic Soil Carbon Stock Changes

Soils contain both organic and inorganic forms of C, but soil organic C (SOC) stocks are the main source and sink for atmospheric CO_2 in most soils. Changes in inorganic C stocks are typically minor. In addition, SOC is the dominant organic C pool in cropland ecosystems, because biomass and dead organic matter have considerably less C and those pools are relatively ephemeral. IPCC (2006) recommends reporting changes in SOC stocks due to agricultural land-use and management activities on mineral and organic soils.[27]

Typical well-drained mineral soils contain from 1 to 6 percent organic C by weight, although mineral soils that are saturated with water for substantial periods during the year may contain significantly more C (NRCS 1999). When mineral soils undergo conversion from their native state to agricultural uses, as much as half of the SOC can be lost to the atmosphere. The rate and ultimate magnitude of C loss will depend on pre-conversion conditions, conversion method and subsequent management practices, climate, and soil type. In the tropics, 40 to 60 percent of the C loss generally occurs

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[27] CO_2 emissions associated with liming are also estimated but are included in a separate section of the report.

within the first 10 years following conversion; C stocks continue to decline in subsequent decades but at a much slower rate. In temperate regions, C loss can continue for several decades, reducing stocks by 20 to 40 percent of native C levels. 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. However, land use, management, and other conditions may change before the new equilibrium is reached. The quantity and quality of organic matter inputs and their rate of decomposition are determined by the combined interaction of climate, soil properties, and land use. Land use and 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 flux of C to or from the pool of soil C.

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), forming under inundated conditions, in which minimal decomposition of plant residue occurs. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil, which accelerates the rate of decomposition and CO_2 emissions. Because of the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time. The rate of CO_2 emissions varies depending on climate and composition (i.e., decomposability) of the organic matter. Also, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests, due to deeper drainage and more intensive management practices in cropland (Armentano and Verhoeven 1990, as cited in IPCC/UNEP/OECD/IEA 1997). C losses are estimated from drained organic soils under both grassland and cropland management in this Inventory.

Cropland Remaining Cropland includes all cropland in an inventory year that had been cropland for the last 20 years[28] according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, the area of *Cropland Remaining Cropland* changes through time with land-use change. CO_2 emissions and removals[29] due to changes in mineral soil C stocks are estimated using a Tier 3 approach for the majority of annual crops. A Tier 2 IPCC method is used for the remaining crops (vegetables, tobacco, perennial/horticultural crops, and rice) not included in the Tier 3 method. In addition, a Tier 2 method is used for very gravelly, cobbly or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles or shale) and for additional changes in mineral soil C stocks that were not addressed with the Tier 2 or 3 approaches (i.e., change in C stocks after 2003 due to Conservation Reserve Program enrollment). Emissions from organic soils are estimated using a Tier 2 IPCC method.

Of the two sub-source categories, land use and land management of mineral soils was the most important component of total net C stock change between 1990 and 2007 (see Table 7-17 and Table 7-18). In 2007, mineral soils were estimated to remove 47.3 Tg CO_2 Eq. (12.9 Tg C). This rate of C storage in mineral soils represented about a 17 percent decrease in the rate since the initial reporting year of 1990. Emissions from organic soils were 27.7 Tg CO_2 Eq. (7.5 Tg C) in 2007. In total, U.S. agricultural soils in *Cropland Remaining Cropland* removed approximately 19.7 Tg CO_2 Eq. (5.4 Tg C) in 2007.

The net reduction in soil carbon accumulation over the time series (33 percent for 2007, relative to 1990) was largely due to the declining influence of annual cropland enrolled in the Conservation Reserve Program, which began in the late 1980s. However, there were still positive increases in C stocks from land enrolled in the reserve program, as well as 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).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-5 and Figure 7-6. The highest rates of net C accumulation in mineral soils occurred in the Midwest, which is the area with the largest amounts of cropland managed with conservation tillage. Rates were also high in the Great Plains due to enrollment in the Conservation Reserve Program.

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[28] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

[29] Note that removals occur through crop and forage uptake of CO_2 into biomass C that is later incorporated into soil pools.

Table 7-17: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils[a]	(56.8)	(50.6)	(57.9)	(45.9)	(46.8)	(47.3)
Organic Soils	27.4	27.7	27.7	27.7	27.7	27.7
Total Net Flux[a]	**(29.4)**	**(22.9)**	**(30.2)**	**(18.3)**	**(19.1)**	**(19.7)**

[a] Preliminary estimates that will be finalized after public review period following completion of quality control measures.

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-18: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (Tg C)

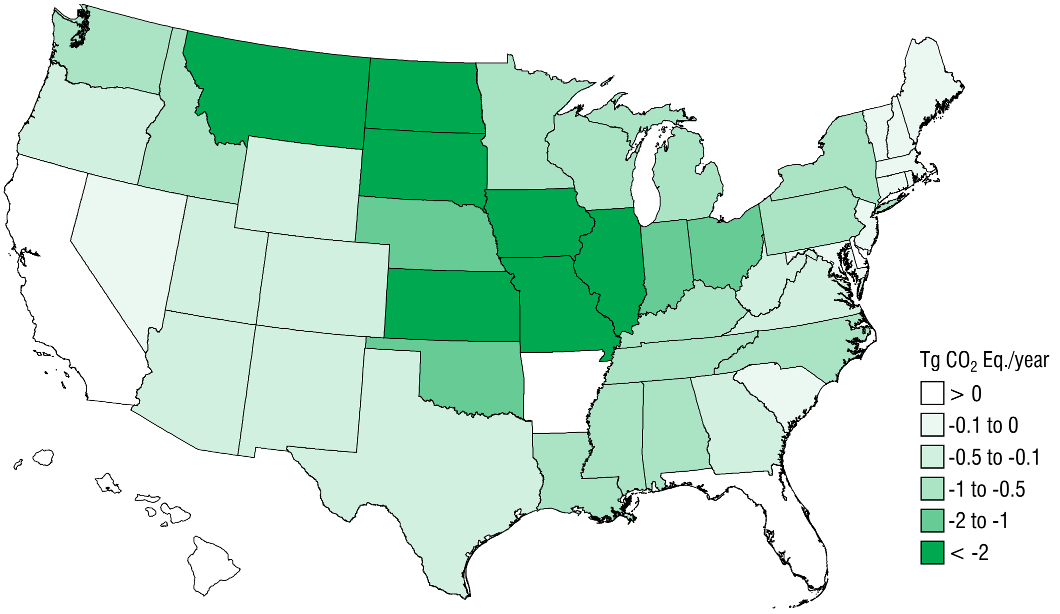
Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils[a]	(15.5)	(13.8)	(15.8)	(12.5)	(12.8)	(12.9)
Organic Soils	7.5	7.5	7.5	7.5	7.5	7.5
Total Net Flux[a]	**(8.0)**	**(6.3)**	**(8.2)**	**(5.0)**	**(5.2)**	**(5.4)**

[a] Preliminary estimates that will be finalized after public review period following completion of quality control measures.

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Figure 7-5

Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2007, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

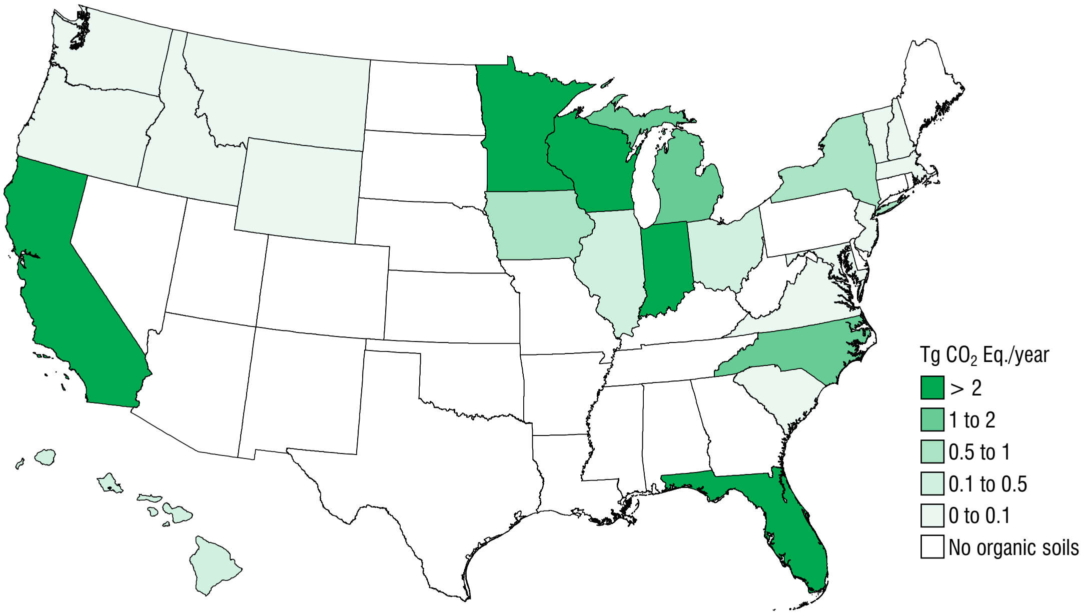
Emission rates from drained organic soils were highest along the southeastern coastal region, in the northeast central United States surrounding the Great Lakes, and along the central and northern portions of the West Coast.

Methodology

The following section includes a description of the methodology used to estimate changes in soil C stocks due to: (1) agricultural land-use and management activities on

Figure 7-6

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2007, *Cropland Remaining Cropland*



Note: Values greater than zero represent emissions.

mineral soils; and (2) agricultural land-use and management activities on organic soils for *Cropland Remaining Cropland*.

Soil C stock changes were 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 *National Resources Inventory* (NRI) survey (USDA-NRCS 2000). The NRI is a statistically-based sample of all non-federal land, and includes approximately 260,000 points in agricultural land for the conterminous United States and Hawaii.[30] Each point is associated with an "expansion factor" that allows scaling of C stock changes 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 for 4 out of 5 years in the cycle (i.e., 1979–1982, 1984–1987, 1989–1992, and 1994–1997). However, the NRI program began collecting annual data in 1998, and data are currently available through 2003. NRI points were classified as *Cropland Remaining Cropland* in a given year between 1990 and 2007 if the land use had been cropland for 20 years.[31] Cropland includes all land used to produce food and fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was used to estimate C stock changes for mineral soils used to produce a majority of annual crops in the United States. The remaining crops on mineral soils were estimated using an IPCC Tier 2 method (Ogle et al. 2003), including vegetables, tobacco, perennial/horticultural crops, rice, and crops rotated with these crops. The Tier 2 method was also used for very gravelly, cobbly or shaley soils (greater than 35 percent by

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[30] NRI points were classified as agricultural if under grassland or cropland management between 1990 and 2003.

[31] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

volume). Mineral SOC stocks were estimated using a Tier 2 method for these areas, because the Century model used for the Tier 3 method has not been fully tested to address its adequacy for estimating C stock changes associated with certain crops and rotations, as well as cobbly, gravelly or shaley soils. An additional stock change calculation was made for mineral soils using Tier 2 emission factors, accounting for enrollment patterns in the Conservation Reserve Program after 2003, which was not addressed by the Tier 3 methods.

Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described below and in Annex 3.13.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), which simulates the dynamics of C and other elements in cropland, grassland, forest, and savanna ecosystems. It uses monthly weather data as an input, along with information about soil physical properties. Input data on land use and management are specified at monthly 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 computes net primary productivity and C additions to soil, soil temperature, and water dynamics, in addition to turnover, stabilization, and mineralization of soil organic matter C and nutrient (N, K, S) elements. This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC, because the simulation model treats changes as continuous over time rather than the simplified discrete changes represented in the default method (see Box 7-2 for additional information). National estimates were obtained by simulating historical land-use and management patterns as recorded in the USDA *National Resources Inventory* (NRI) survey.

Additional sources of activity data were used to supplement the land-use information from NRI. The Conservation Technology Information Center (CTIC 1998) provided annual data on tillage activity at the county level since 1989, with adjustments 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 were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to cropland during 1997 were 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 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area. The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management section (Section 6.2) and annex (Annex 3.10).

Manure amendments were an input to the Century Model based on manure N available for application from all managed or unmanaged systems except Pasture/Range/Paddock.[32] Data on the county-level N available for application were estimated for managed systems based on the total amount of N excreted in manure minus N losses and including the addition of N from bedding materials. N losses include direct nitrous oxide emissions, volatilization of ammonia and NO_x, runoff and leaching, and poultry manure used as a feed supplement. More information on these losses is available in the description of the Manure Management source category. Animal-specific bedding factors were set equal to IPCC default factors (IPCC 2006). For unmanaged systems, it is assumed that no N losses or additions occur.

Monthly weather data were used as an input in the model simulations, based on an aggregation of gridded weather data to the county scale from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) database (Daly et al. 1994). Soil attributes, which were obtained from an NRI database, were assigned based on field visits and soil series descriptions. Each NRI point was run 100 times as part of the uncertainty assessment, yielding a total of over 18 million

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[32] Pasture/Range/Paddock manure additions to soils are addressed in the *Grassland Remaining Grassland* and *Land Converted to Grassland* categories.

Box 7-2: Tier 3 Inventory for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to inventory soil C stock changes on the majority of agricultural land with mineral soils. This approach entails several fundamental differences compared to the IPCC Tier 1 or 2 methods, which are based on a classification of land areas into a number of discrete classes based on a highly aggregated classification of climate, soil, and management (i.e., only six climate regions, seven soil types and eleven management systems occur in U.S. agricultural land under the IPCC classification). Input variables to the Tier 3 model, including climate, soils, and management activities (e.g., fertilization, crop species, tillage, etc.), are represented in considerably more detail both temporally and spatially, and exhibit multi-dimensional interactions through the more complex model structure compared with the IPCC Tier 1 or 2 approach. The spatial resolution of the analysis is also finer in the Tier 3 method compared to the lower tier methods as implemented in the United States for previous Inventories (e.g., 3,037 counties versus 181 Major Land Resource Areas (MLRAs), respectively).

In the Century model, soil C dynamics (and CO_2 emissions and uptake) are treated as continuous variables, which change on a monthly time step. C emissions and removals are an outcome of plant production and decomposition processes, which are simulated in the model structure. Thus, changes in soil C stocks are influenced by not only changes in land use and management but also inter-annual climate variability and secondary feedbacks between management activities, climate and soils as they affect primary production and decomposition. This latter characteristic constitutes one of the greatest differences between the methods, and forms the basis for a more complete accounting of soil C stock changes in the Tier 3 approach compared with Tier 2 methodology.

Because the Tier 3 model simulates a continuous time period rather than as an equilibrium step change used in the IPCC methodology (Tier 1 and 2), the Tier 3 model addresses the delayed response of the soil to management and land-use changes. Delayed responses can occur due to variable weather patterns and other environmental constraints that interact with land use and management and affect the time frame over which stock changes occur. Moreover, the Tier 3 method also accounts for the overall effect of increasing yields and, hence, C input to soils that have taken place across management systems and crop types within the United States. Productivity has increased by 1 to 2 percent annually over the past 4 to 5 decades for most major crops in the United States (Reilly and Fuglie 1998), which is believed to have led to increases in cropland soil C stocks (e.g., Allmaras et al. 2000). This is a major difference from the IPCC-based Tier 1 and 2 approaches, in which trends in soil C stocks only capture discrete changes in management and/or land use, rather than a longer term trend such as gradual increases in crop productivity.

simulation runs for the analysis. C stock estimates from Century were adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Ogle et al. 2007). C stocks and 95 percent confidence intervals were estimated for each year between 1990 and 2003, but C stock changes from 2004 to 2007 were assumed to be similar to 2003 because no additional activity data are currently available from the NRI for the latter years.

Tier 2 Approach

In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity were used to classify land area to apply appropriate stock change factors. MLRAs formed the base spatial unit for mapping climate regions in the United States; each MLRA represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981). MLRAs were classified into climate regions according to the IPCC categories using the PRISM climate database of Daly et al. (1994).

Reference C stocks were estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2003, 2006). Changing the reference condition was necessary because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than those that are not considered cultivated cropland.

U.S.-specific stock change factors were derived from published literature to determine the impact of management practices on SOC storage, including changes in tillage, cropping rotations and intensification, and land-use change between cultivated and uncultivated conditions (Ogle et al. 2003, Ogle et al. 2006). U.S. factors associated with organic matter amendments were not estimated because of an insufficient number of studies to analyze those impacts. Instead, factors from IPCC (2003) were used to estimate the effect of those activities. Euliss and Gleason (2002) provided the data for computing the change in SOC storage resulting from restoration of wetland enrolled in the Conservation Reserve Program.

Similar to the Tier 3 Century method, activity data were primarily based on the historical land-use/management patterns recorded in the NRI. Each NRI point was classified by land use, soil type, climate region (using PRISM data, Daly et al. 1994) and management condition. Classification of cropland area by tillage practice was based on data from the Conservation Tillage Information Center (CTIC 1998, Towery 2001) as described above. Activity data on wetland restoration of Conservation Reserve Program land were obtained from Euliss and Gleason (2002). Manure N amendments over the inventory time period were 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 previous methodology subsection on the Tier 3 analysis for mineral soils.

Combining information from these data sources, SOC stocks for mineral soils were estimated 50,000 times for 1982, 1992, and 1997, using a Monte Carlo simulation approach and the 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). The annual C flux for 1990 through 1992 was determined by calculating the average annual change in stocks between 1982 and 1992; annual C flux for 1993 through 2007 was determined by calculating the average annual change in stocks between 1992 and 1997.

Additional Mineral C Stock Change

Annual C flux estimates for mineral soils between 1990 and 2007 were adjusted to account for additional C stock changes associated with gains or losses in soil C after 2003 due to changes in Conservation Reserve Program enrollment. The change in enrollment acreage relative to 2003 was based on data from USDA-FSA (2007) for 2004 through 2007, and the differences in mineral soil areas were 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 estimations using the IPCC method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), with U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Similar to the Tier 2 analysis for mineral soils, the final estimates included a measure of uncertainty as determined from the Monte Carlo simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Cropland Remaining Cropland* areas from the 1997 *National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2007.

Uncertainty

Uncertainty associated with the *Cropland Remaining Cropland* land-use category was addressed for changes in agricultural soil C stocks (including both mineral and organic soils). Uncertainty estimates are presented in Table 7-19 for

Table 7-19: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (Tg CO_2 Eq. and Percent)

Source	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(42.3)	(69.6)	(15.1)	-64%	+64%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.0)	(6.9)	0.8	-127%	+128%
Mineral Soil C Stocks: Cropland Remaining Cropland (Change in CRP enrollment relative to 2003)	(2.0)	(3.0)	(1.0)	-50%	+50%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	27.7	15.8	36.9	-43%	+33%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(19.7)**	**(49.6)**	**9.4**	**-152%**	**+148%**

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

mineral soil C stocks and organic soil C stocks disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with IPCC (2006). The combined uncertainty was calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. More details on how the individual uncertainties were developed are in Annex 3.13. The combined uncertainty for soil C stocks in *Cropland Remaining Cropland* ranged from 152 percent below to 148 percent above the 2007 stock change estimate of -19.7 Tg CO_2 Eq.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled throughout the inventory process. Several errors were found in the implementation of the new annual NRI data, mostly involving problems in scheduling crops and practices with the more detailed histories; corrective actions were taken to deal with the errors. As discussed in the uncertainty section, results were compared to field measurements, and a statistical relationship was developed to assess uncertainties in the model's predictive capability. The comparisons included over 40 long-term experiments, representing about 800 combinations of management treatments across all of the sites (Ogle et al. 2007). Inventory reporting forms and text were reviewed and revised as needed to correct transcription errors.

Recalculations Discussion

Annual survey data from the USDA *National Resources Inventory* (NRI) were incorporated into this year's estimates. This resulted in several changes to the inventory methods:

First, the availability of new data extended the time series of activity data beyond 1997 to 2003.[33] In previous Inventories, activity data were only available through 1997, and so subsequent years were treated as the same land use practice occurring in 1997.

Second, annual area data, rather than area data that had been collected in 5-year increments, were used to estimate soil C stock changes, leading to more accurate estimates.

Third, each NRI point was simulated separately, instead of simulating clusters of points that had common cropping rotation histories and soil characteristics in a county. More importantly, the exact cropping histories were simulated, instead of generalized cropping rotations (e.g., wheat-fallow, corn-soybean).

Overall, the recalculations resulted in an average annual decline in soil organic C stocks of 12.5 Tg CO_2 Eq. for the period 1990 through 2006, compared to the previous Inventory. Uncertainties were also higher in this year's Inventory because soil C stock changes were estimated for each year from new annual NRI data. Previous Inventories took an average of changes over 5-year periods.

CO_2 Emissions from Liming of Agricultural Soils

IPCC (2006) recommends reporting CO_2 emissions from lime additions (in the form of crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to agricultural soils. Limestone and dolomite are added by land managers to ameliorate acidification. When these compounds come in contact with acid soils, they degrade, thereby generating CO_2. The rate and ultimate magnitude of degradation of applied limestone and dolomite depends on the soil conditions, climate regime, and the type of mineral applied. Emissions from liming have fluctuated over the past sixteen years, ranging from 3.8 Tg CO_2 Eq. to 5.0 Tg CO_2 Eq. In 2007, liming of agricultural soils in the United States resulted in emissions of 4.1 Tg CO_2 Eq. (1.1 Tg C), representing about a 13 percent decrease in emissions since 1990 (see Table 7-20 and Table 7-21). The trend is driven entirely by the amount of lime and dolomite estimated to have been applied to soils over the time period.

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[33] Note that the new NRI data were only used in the Tier 3 estimates. The Tier 2 estimates still use data from the 1997 *National Resources Inventory*, but will be updated in the future.

Table 7-20: CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq.)

Source	1990	1995	2000	2005	2006	2007
Liming of Agricultural Soils[a]	4.7	4.4	4.3	4.3	4.2	4.1

[a] Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-21: CO_2 Emissions from Liming of Agricultural Soils (Tg C)

Source	1990	1995	2000	2005	2006	2007
Liming of Agricultural Soils[a]	1.3	1.2	1.2	1.2	1.2	1.1

[a] Also includes emissions from liming on *Land Converted to Cropland*, *Grassland Remaining Grassland*, *Land Converted to Grassland*, and *Settlements Remaining Settlements*.

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Methodology

CO_2 emissions from degradation of limestone and dolomite applied to agricultural soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite applied (see Table 7-22) were multiplied by CO_2 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 agricultural lime that may leach through the soil and travel by rivers to the ocean (West and McBride 2005). This analysis of lime dissolution is based on liming occurring in the Mississippi River basin, where the vast majority of all U.S. liming takes place (West 2008). U.S. liming that does not occur in the Mississippi River basin tends to occur under similar soil and rainfall regimes, and, thus, the emission factor is appropriate for use across 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, b; USGS 2007, 2008). 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 crushed stone manufacturers. Because some manufacturers were reluctant to provide information, 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).

The "unspecified" and "estimated" amounts of crushed limestone and dolomite applied to agricultural soils were calculated by multiplying the percentage of total "specified" limestone and dolomite production applied to agricultural 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 agricultural soils (as opposed to other uses of the stone) was assumed to be proportionate to the amount of "specified" crushed limestone and dolomite that was applied to agricultural soils. In addition, data were not available for 1990, 1992, and 2007 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.

Table 7-22: Applied Minerals (Million Metric Tons)

Source	1990	1995	2000	2005	2006	2007
Limestone	19.01	17.30	15.86	18.09	17.14	16.42
Dolomite	2.36	2.77	3.81	1.85	2.24	2.14

Note: These numbers represent amounts applied to *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland,* and *Settlements Remaining Settlements*.

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 2007 data, the previous year's fractions were applied to a 2007 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2008* (USGS 2008).

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. Since limestone and dolomite activity data are also available at the state level, the national-level estimates reported here were broken out by state, although state-level estimates are not reported here.

Uncertainty

Uncertainty regarding limestone and dolomite activity data inputs was estimated at ±15 percent and assumed to be uniformly distributed around the inventory estimate (Tepordei 2003b). Analysis of the uncertainty associated with the emission factors included the following: the fraction of agricultural 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 accounted for, but should not change the uncertainty associated with CO_2 emissions (West 2005). The uncertainty associated with the fraction of agricultural lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were each modeled as a smoothed triangular distribution between ranges of 0 percent to 100 percent. The uncertainty surrounding these two components largely drives the overall uncertainty estimates reported below. More information on the uncertainty estimates for liming of agricultural soils is contained within the Uncertainty Annex.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 emissions from liming. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-23. CO_2 emissions from liming of agricultural soils in 2007 were estimated to be between 0.22 and 8.30 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 95 percent below to 105 percent above the 2007 emission estimate of 4.05 Tg CO_2 Eq.

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

Several adjustments were made in the current Inventory to improve the results. The quantity of applied minerals reported in the previous Inventory for 2006 has been revised. Consequently, the reported emissions resulting from liming in 2006 have also changed. In the previous Inventory, to estimate 2006 data, the previous year's fractions were

Table 7-23: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming of Agricultural Soils (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming of Agricultural Soils[b]	CO_2	4.1	0.2	8.3	-95%	+105%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[b] Also includes emissions from liming on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland,* and *Settlements Remaining Settlements*.

applied to a 2006 estimate of total crushed stone presented in the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the First Quarter of 2007* (USGS 2007). Since publication of the previous Inventory, the *Minerals Yearbook* has published actual quantities of crushed stone sold or used by producers in the United States in 2006. These values have replaced those used in the previous Inventory to calculate the quantity of minerals applied to soil and the emissions from liming.

CO_2 Emissions from Urea Fertilization

The use of urea ($CO(NH_2)_2$) as fertilizer leads to emissions of CO_2 that was fixed during the industrial production process. Urea in the presence of water and urease enzymes is converted into ammonium (NH_4^+), hydroxyl ion (OH^-), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States totaled 4.0 Tg CO_2 Eq. (1.1 Tg C) in 2007 (Table 7-24 and Table 7-25). Emissions from urea fertilization have fluctuated over the past sixteen years, ranging from 2.3 Tg CO_2 Eq. to 4.0 Tg CO_2 Eq.

Methodology

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The annual amounts of urea fertilizer applied (see Table 7-26) were derived from state-level fertilizer sales data provided in *Commercial Fertilizers* (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2008) and were multiplied by the default IPCC (2006) emission factor of 0.20, which is equal to the C content of urea on an atomic weight basis. Because fertilizer sales data are reported in fertilizer years (July through June), a calculation was performed to convert the data to calendar years (January through December). According to historic monthly fertilizer use data (TVA 1992b), 65 percent of total fertilizer used in any fertilizer year is applied between January through June of that calendar year, and 35 percent of total fertilizer used in any fertilizer year is applied between July through December of the previous calendar year. Fertilizer sales data for the 2008 fertilizer year were not available in time for publication. Accordingly, July through December 2007 fertilizer consumption was estimated by calculating the percent change in urea use from January through June 2006

Table 7-24: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg CO_2 Eq.)

Source	1990	1995	2000	2005	2006	2007
Urea Fertilization[a]	2.4	2.7	3.2	3.5	3.7	4.0

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-25: CO_2 Emissions from Urea Fertilization in *Cropland Remaining Cropland* (Tg C)

Source	1990	1995	2000	2005	2006	2007
Urea Fertilization[a]	0.7	0.7	0.9	1.0	1.0	1.1

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

Table 7-26: Applied Urea (Million Metric Tons)

	1990	1995	2000	2005	2006	2007
Urea Fertilization[a]	3.30	3.62	4.38	4.78	4.98	5.39

[a] Also includes emissions from urea fertilization on *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.

Note: Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only.

to July through December 2006. This percent change was then multiplied by the January through June 2007 data to estimate July through December 2007 fertilizer use. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States.

Uncertainty

Uncertainty estimates are presented in Table 7-27 for Urea Fertilization. A Tier 2 Monte Carlo analysis was completed. The largest source of uncertainty was the default emission factor, which assumes that 100 percent of the C applied to soils is ultimately emitted into the environment as CO_2. This factor does not incorporate the possibility that some of the C may be retained in the soil. The emission estimate is, thus, likely to be high. In addition, each urea consumption data point has an associated uncertainty. Urea for non-fertilizer use, such as aircraft deicing, may be included in consumption totals; it was determined through personal communication with Fertilizer Regulatory Program Coordinator David L. Terry (2007), however, that this amount is most likely very small. Research into aircraft deicing practices also confirmed that urea is used minimally in the industry; a 1992 survey 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 MT per year, or less than 0.07 percent of the fertilizer total for 2007 (Itle 2009). Lastly, there is uncertainty surrounding the assumptions behind the calculation that converts fertilizer years to calendar years. CO_2 emissions from urea fertilization of agricultural soils in 2007 were estimated to be between 2.3 and 4.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 4 percent above the 2006 emission estimate of 4.0 Tg CO_2 Eq.

Table 7-27: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	4.0	2.3	4.1	-43%	+4%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: These numbers represent amounts applied to all agricultural land, including *Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, Settlements Remaining Settlements,* and *Forest Land Remaining Forest Land*.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation. Inventory reporting forms and text were reviewed. No errors were found.

Recalculations Discussion

July to December 2006 urea application was updated with newly available data for fertilizer year 2007, and the 2006 emission estimate was revised accordingly. (In the previous Inventory, the application for this period was calculated based on application during July to December 2005.) No other recalculations were needed, and the rest of the time series remains the same as estimated in the previous Inventory.

Planned Improvements

The primary planned improvement is to investigate using a Tier 2 or Tier 3 approach, which would utilize country-specific information to estimate a more precise emission factor.

7.5. Land Converted to Cropland (IPCC Source Category 5B2)

Land Converted to Cropland includes all cropland in an inventory year that had been another land use at any point during the previous 20 years[34] according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, lands are retained in this category for 20 years as recommended

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[34] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications were based on less than 20 years from 1990 to 2001.

by the IPCC guidelines (IPCC 2006) unless there is another land-use change. Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Cropland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. The IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[35]

Land-use and management of mineral soils in *Land Converted to Cropland* led to losses of soil C during the early 1990s but losses declined slightly through the latter part of the time series (Table 7-28 and Table 7-29). The total rate of change in soil C stocks was 5.9 Tg CO_2 Eq. (1.6 Tg C) in 2007. Mineral soils were estimated to lose 3.3 Tg CO_2 Eq. (0.9 Tg C) in 2007, while drainage and cultivation of organic soils led to annual losses of 2.6 Tg CO_2 Eq. (0.7 Tg C) in 2007.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils for *Land Converted to Cropland* is displayed in Figure 7-7 and Figure 7-8. While a large portion of the United States had net losses in soil C for *Land Converted to Cropland*, there were some notable areas with net C accumulation in the Great Plains, Midwest, and mid-Atlantic states. These areas were gaining C following conversion, because the land had been brought into hay production, including grass and legume hay, leading to enhanced plant production relative to the previous land use, and thus higher C input to the soil. Emissions from organic soils were largest in California, Florida and the upper Midwest, which coincided with largest concentrations of cultivated organic soils in the United States.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils 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 3.13.

Soil C stock changes were estimated for *Land Converted to Cropland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a

Table 7-28: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils	(0.3)	0.3	(0.3)	3.3	3.3	3.3
Organic Soils	2.4	2.6	2.6	2.6	2.6	2.6
Total Net Flux	**2.2**	**2.9**	**2.4**	**5.9**	**5.9**	**5.9**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-29: Net CO_2 Flux from Soil C Stock Changes in *Land Converted to Cropland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils	(0.1)	0.1	(0.1)	0.9	0.9	0.9
Organic Soils	0.7	0.7	0.7	0.7	0.7	0.7
Total Net Flux	**0.6**	**0.8**	**0.6**	**1.6**	**1.6**	**1.6**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

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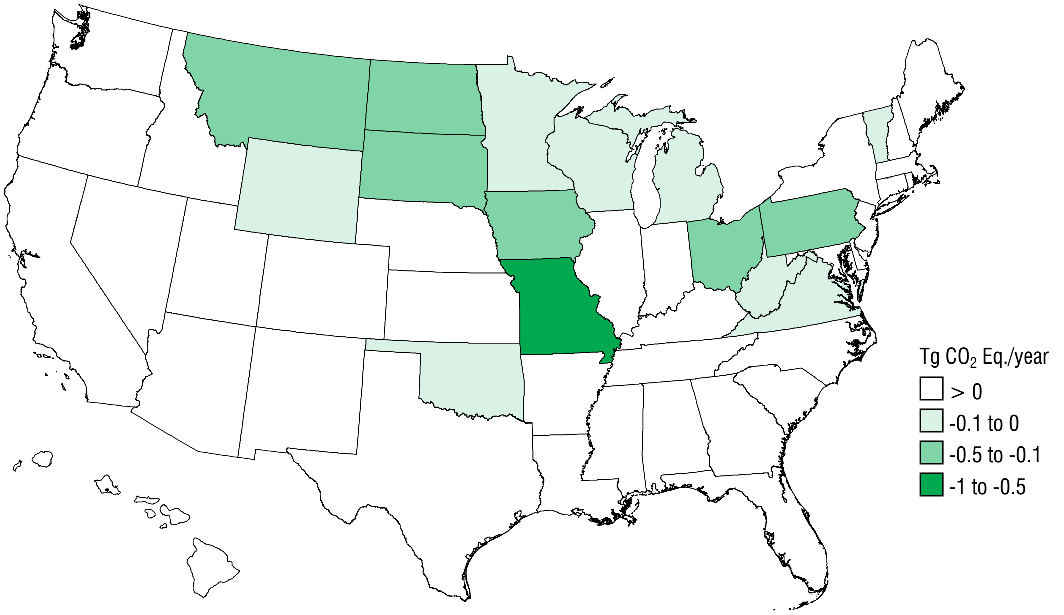
[35] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Figure 7-7

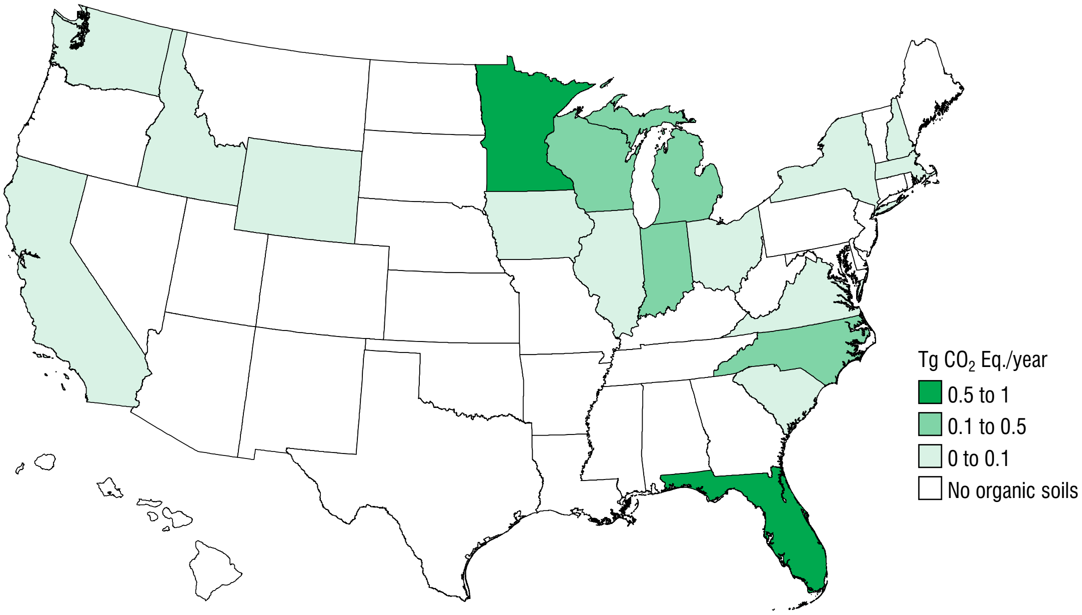
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2007, *Land Converted to Cropland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 Inventory computations. See Methodology for additional details.

Figure 7-8

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2007, *Land Converted to Cropland*



Note: Values greater than zero represent emissions.

5-year cycle beginning in 1982. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Land Converted to Cropland* in a given year between 1990 and 2007 if the land use was cropland but had been another use during the previous 20 years.[36] Cropland includes all land used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage).

Mineral Soil Carbon Stock Changes

A Tier 3 model-based approach was used to estimate C stock changes for soils on *Land Converted to Cropland* used to produce a majority of all crops. Soil C stock changes on the remaining soils were estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce vegetables, tobacco, perennial/horticultural crops, and rice; land on very gravelly, cobbly or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[37]

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model for the Tier 3 methods. National estimates were obtained by using the model to simulate historical land-use change patterns as recorded in the USDA *National Resources Inventory* (USDA-NRCS 2000). The methods used for *Land Converted to Cropland* are the same as those described in the Tier 3 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 3 methods section and Annex 3.13 for additional information).

Tier 2 Approach

For the mineral soils not included in the Tier 3 analysis, SOC stock changes were estimated using a Tier 2 Approach for *Land Converted to Cropland* as described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils (see *Cropland Remaining Cropland* Tier 2 methods section for additional information).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Cropland* were estimated using the Tier 2 method provided in IPCC (2003, 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 simulation with 50,000 iterations. Emissions were based on the 1992 and 1997 *Land Converted to Cropland* areas from the 1997 *National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2007.

Uncertainty

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches was based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Cropland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-30 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with 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 *Land Converted to Cropland* was estimated to be 40 percent below and 36 percent above the inventory estimate of 5.9 Tg CO_2 Eq.

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[36] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

[37] Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2000).

Table 7-30: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Cropland* (Tg CO_2 Eq. and Percent)

Source	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Cropland, Tier 3 Inventory Methodology	(0.8)	(1.5)	(0.1)	-84%	+84%
Mineral Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	4.1	2.3	5.8	-44%	+41%
Organic Soil C Stocks: Land Converted to Cropland, Tier 2 Inventory Methodology	2.6	1.2	3.7	-53%	+41%
Combined Uncertainty for Flux Associated with Soil Carbon Stock Change in Land Converted to Cropland	**5.9**	**3.5**	**8.1**	**-40%**	**+36%**

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

QA/QC and Verification

See QA/QC and Verification section under *Cropland Remaining Cropland*.

Recalculations Discussion

Annual survey data from the USDA *National Resources Inventory* (NRI) were incorporated into the current Inventory. This resulted in several changes to the inventory methods:

First, the availability of new data extended the time series of activity data beyond 1997 to 2003.[38] In previous Inventories, activity data were only available through 1997, and so subsequent years were treated as the same land use practice occurring in 1997.

Second, annual area data, rather than area data that had been collected in 5-year increments, were used to estimate soil C stock changes, leading to more accurate estimates.

Third, each NRI point was simulated separately, instead of simulating clusters of points that had common land use/cropping rotation histories and edaphic characteristics in a county. More importantly, the exact cropping histories were simulated, instead of generalized cropping rotations (e.g., wheat-fallow, corn-soybean).

Fourth, NRI area data were reconciled with the forest area estimates in the Forest Inventory and Analysis (FIA) dataset, and were incorporated into the estimation of soil C stock changes. The reconciliation led to adjustments in the grassland areas in the NRI dataset, including *Land Converted to Cropland*[39] (i.e., *Grassland and Wetlands Converted to Cropland*).

Overall, these recalculations resulted in an average annual increase in soil C stocks of 8.5 Tg CO_2 Eq. for soil C stock changes in *Land Converted to Cropland* over the time series from 1990 through 2006, compared to the previous Inventory.

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties related to the structure of the Century model for *Land Converted to Cropland*, but this is a planned improvement. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.6. Grassland Remaining Grassland (IPCC Source Category 5C1)

Grassland Remaining Grassland includes all grassland in an inventory year that had been grassland for the previous

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[38] Note that the new NRI data were only used in the Tier 3 inventory. The Tier 2 portion of the inventory still used data from the 1997 *National Resources Inventory*, but will be updated in the future.

[39] NRI area data for forest lands was adjusted the match the forest area estimates in the Forest Inventory and Analysis dataset. In order to maintain the same total area, the area data for grasslands and wetlands in the NRI were adjusted to offset the increase or decrease in the forest land area (see section on Representation of U.S. Land Base for more information).

20 years[40] according to the USDA NRI land use survey (USDA-NRCS 2000). Background on agricultural C stock changes is provided in the *Cropland Remaining Cropland* section and will only be summarized here for *Grassland Remaining Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared to soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[41]

Land-use and management of mineral soils in *Grassland Remaining Grassland* increased soil C, while organic soils lost relatively small amounts of C in each year 1990 through 2007. Due to the pattern for mineral soils, the overall trend were gains in soil C over the time series although the rates varied from year to year, with a net removal of 4.7 Tg CO_2 Eq. (5.4 Tg C) in 2007 (Table 7-31 and Table 7-32). However, there was considerable variation driven by variability in weather patterns over the time series. Overall, flux rates declined by 42.1 Tg CO_2 Eq. (11.5 Tg C) when comparing the net change in soil C for 1990 and 2007.

The spatial variability in annual CO_2 flux associated with C stock changes in mineral and organic soils is displayed in Figure 7-9 and Figure 7-10. Grassland gained soil organic C in several regions during 2007, including the Northeast, Midwest, Southwest, and far western states; although these were relatively small increases in C on a per-hectare basis. Similar to *Cropland Remaining Cropland*, emission rates from drained organic soils were highest along the southeastern coastal region, in the northeast central United States surrounding the Great Lakes, and along the central and northern portions of the West Coast.

Methodology

The following section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral and organic soils for *Grassland Remaining Grassland*. 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 3.13.

Table 7-31: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils	(50.6)	(40.1)	(55.1)	(8.3)	(8.3)	(8.4)
Organic Soils	3.9	3.7	3.7	3.7	3.7	3.7
Total Net Flux	**(46.7)**	**(36.4)**	**(51.4)**	**(4.6)**	**(4.6)**	**(4.7)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-32: Net CO_2 Flux from Soil C Stock Changes in *Grassland Remaining Grassland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils	(13.8)	(10.9)	(15.0)	(2.3)	(2.3)	(2.3)
Organic Soils	1.1	1.0	1.0	1.0	1.0	1.0
Total Net Flux	**(12.7)**	**(9.9)**	**(14.0)**	**(1.3)**	**(1.3)**	**(1.3)**

Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

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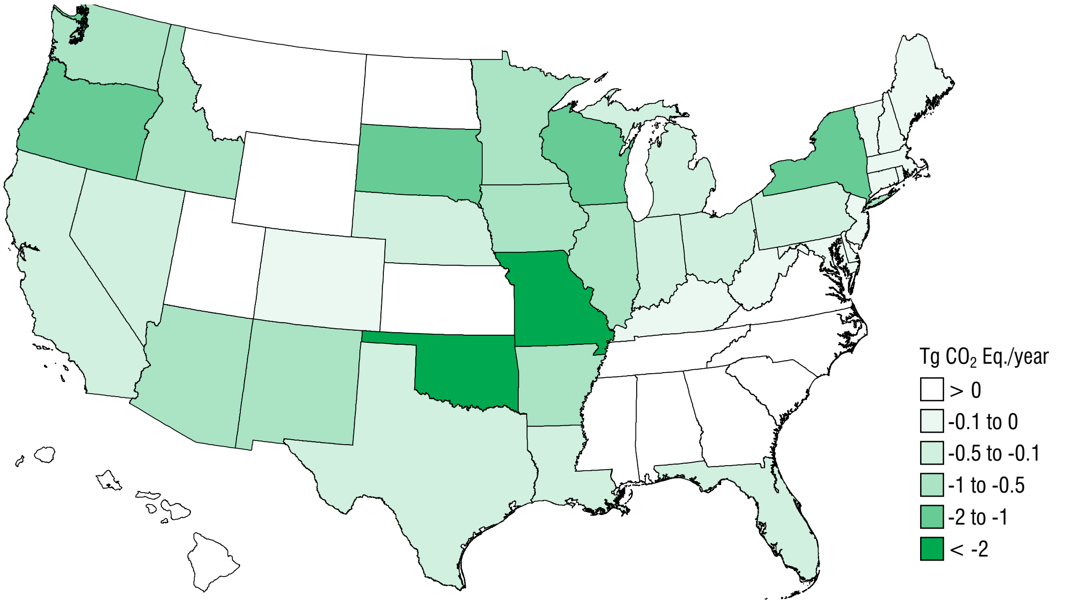
[40] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifcations were based on less than 20 years from 1990 to 2001.

[41] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Figure 7-9

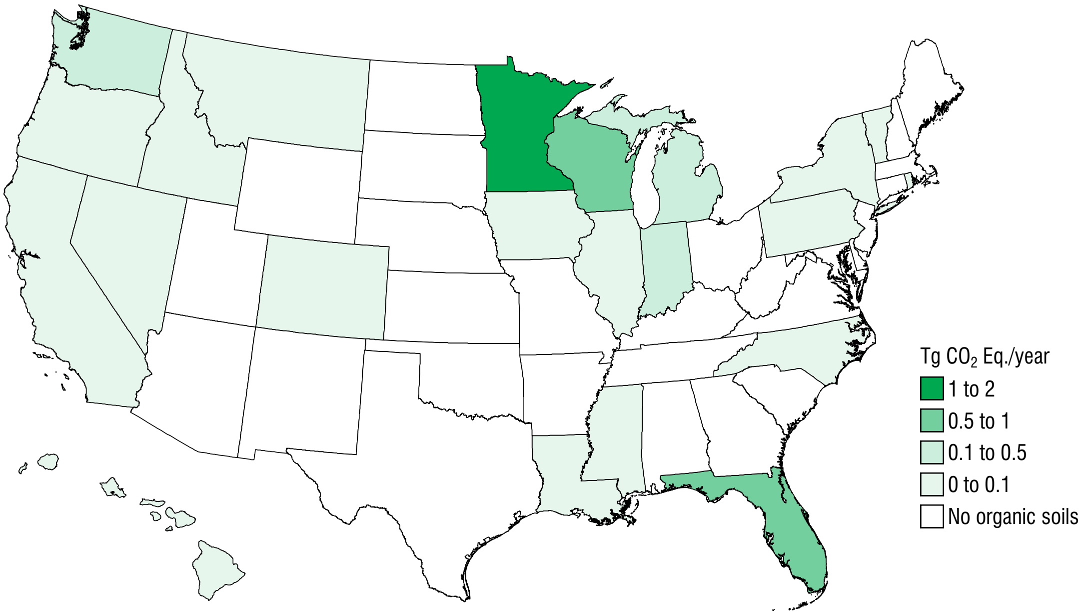
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2007, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure 7-10

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2007, *Grassland Remaining Grassland*



Note: Values greater than zero represent emissions.

Soil C stock changes were estimated for *Grassland Remaining Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). 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. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Grassland Remaining Grassland* in a given year between 1990 and 2007 if the land use had been grassland for 20 years.[42] Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was used to estimate C stock changes for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils were 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 soil organic C stocks and stock changes for *Grassland Remaining Grassland* were estimated using the Century biogeochemical model, as described in *Cropland Remaining Cropland*. Historical land-use and management patterns were used in the Century simulations as recorded in the USDA *National Resources Inventory* (NRI) survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and National Agricultural Statistics Service (NASS 1992, 1999, 2004). Frequency and rates of manure application to grassland during 1997 were 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 were used to adjust the area amended with manure (see Annex 3.13 for further details). Greater availability of managed manure N relative to 1997 was, thus, assumed to increase the area amended with manure, while reduced availability of manure N relative to 1997 was assumed to reduce the amended area.

The amount of manure produced by each livestock type was calculated for managed and unmanaged waste management systems based on methods described in the Manure Management Section (Section 6.2) and Annex (Annex 3.10). In contrast to manure amendments, Pasture/Range/Paddock (PRP) manure N deposition was estimated internally in the Century model, as part of the grassland system simulations (i.e., PRP manure deposition was not an external input into the model). See the Tier 3 methods in *Cropland Remaining Cropland* section for additional discussion on the Tier 3 methodology for mineral soils.

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 (see *Cropland Remaining Cropland* Tier 2 methods section and Annex 3.13 for additional information).

Additional Mineral C Stock Change Calculations

Annual C flux estimates for mineral soils between 1990 and 2007 were adjusted to account for additional C stock changes associated with sewage sludge amendments using a Tier 2 method. Estimates of the amounts of sewage sludge N applied to agricultural land were derived from national data on sewage sludge generation, disposition, and nitrogen content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, were obtained from an EPA report (EPA 1999) and estimates for 2004 were obtained from an independent national biosolids survey (NEBRA 2007). These values were linearly interpolated to estimate values for the intervening years. N application rates from Kellogg et al. (2000) were used to determine the amount of area receiving sludge amendments. Although sewage sludge

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[42] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began. Therefore, the classification prior to 2002 was based on less than 20 years of recorded land-use history for the time series.

can be added to land managed for other land uses, it was assumed that agricultural amendments occur in grassland. Cropland is assumed to rarely be amended with sewage sludge due to the high metal content and other pollutants in human waste. The soil C storage rate was estimated at 0.38 metric tons C per hectare per year for sewage sludge amendments to grassland. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.13 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Grassland Remaining Grassland* areas from the 1997 *National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2007.

Uncertainty

Uncertainty estimates are presented in Table 7-33 for each subsource (i.e., mineral soil C stocks and organic soil C stocks) disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with 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* was estimated to be 54 percent below and 41 percent above the inventory estimate of -4.7 Tg CO_2 Eq.

Uncertainties in Mineral Soil Carbon Stock Changes

The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 3 approach and Tier 2 approach were based on the same method described for *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. See the Tier 3 approach for mineral soils under the *Cropland Remaining Cropland* section for additional discussion.

A ±50 percent uncertainty was assumed for additional adjustments to the soil C stocks between 1990 and 2007 to account for additional C stock changes associated with amending grassland soils with sewage sludge.

Table 7-33: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Grassland Remaining Grassland* (Tg CO_2 Eq. and Percent)

Source	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(7.0)	(7.2)	(6.8)	-2%	+2%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.2)	(0.3)	0.0	-89%	+127%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Sewage Sludge Amendments)	(1.2)	(1.8)	(0.6)	-50%	+50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	3.7	1.2	5.5	-66%	+49%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stock Change in Grassland Remaining Grassland	**(4.7)**	**(7.2)**	**(2.7)**	**-54%**	**+41%**

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

Uncertainties in Soil Carbon Stock Changes for Organic Soils

Uncertainty in C emissions from organic soils was estimated using country-specific factors and a Monte Carlo analysis. Probability distribution functions for emission factors were derived from a synthesis of 10 studies, and combined with uncertainties in the NRI land use and management data for organic soils in the Monte Carlo analysis. See the Tier 2 section under minerals soils of *Cropland Remaining Cropland* for additional discussion.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data were properly handled through the inventory process. Several errors were found in the implementation of the new annual NRI data, mostly involving problems in scheduling crops and practices with the more detailed histories; corrective actions were taken to deal with the errors.

Recalculations Discussion

Annual survey data from the USDA *National Resources Inventory* (NRI) were incorporated into this year's Inventory. This resulted in several changes to the inventory methods:

First, the availability of new data extended the time series of activity data beyond 1997 to 2003.[43] In previous Inventories, activity data were only available through 1997, and so subsequent years were treated as the same land use practice occurring in 1997.

Second, annual area data, rather than area data that had been collected in 5-year increments, were used to estimate soil C stock changes, leading to more accurate estimates.

Third, each NRI point was simulated separately, instead of simulating clusters of points that had common land use histories and edaphic characteristics in a county.

Fourth, NRI area data were reconciled with the forest area estimates in the Forest Inventory and Analysis (FIA) dataset, and were incorporated into the estimation of soil C stock changes. The reconciliation led to adjustments in the grassland areas in the NRI dataset, including *Grassland Remaining Grassland*.[44]

Overall, the recalculations resulted in an average annual increase in soil C stocks of 31 Tg CO_2 Eq. for the time series over the period from 1990 through 2006, compared to the previous Inventory.

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties in Century model results for *Grassland Remaining Grassland*, but this is a planned improvement for the Inventory. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

7.7. Land Converted to Grassland (IPCC Source Category 5C2)

Land Converted to Grassland includes all grassland in an inventory year that had been in another land use at any point during the previous 20 years[45] according to the USDA NRI land use survey (USDA-NRCS 2000). Consequently, lands are retained in this category for 20 years as recommended by IPCC (2006) unless there is another land use change. Background on agricultural C stock changes is provided in *Cropland Remaining Cropland* and will only be summarized here for *Land Converted to Grassland*. Soils are the largest pool of C in agricultural land, and also have the greatest potential for storage or release of C, because biomass and dead organic matter C pools are relatively small and ephemeral compared with soils. IPCC (2006) recommend reporting changes in soil organic C stocks due to: (1) agricultural land-use and management activities on mineral

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[43] Note that the new NRI data were only used in the Tier 3 estimates. The Tier 2 portion of the estimates still used data from the 1997 *National Resources Inventory*, but will be updated in the future.

[44] NRI area data for forest lands was adjusted the match the forest area estimates in the Forest Inventory and Analysis dataset. In order to maintain the same total area, the area data for grasslands and wetlands in the NRI were adjusted to offset the increase or decrease in the forest land area (see section on Representation of U.S. Land Base for more information).

[45] NRI points were classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifcations were based on less than 20 years from 1990 to 2001.

soils, and (2) agricultural land-use and management activities on organic soils.[46]

Land-use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil C stocks from 1990 through 2007, which was largely due to annual cropland conversion to pasture (see Table 7-34 and Table 7-35). For example, the stock change rates were estimated to remove 22.7 Tg CO_2 Eq./yr (6.2 Tg C) and 27.6 Tg CO_2 Eq./yr (7.5 Tg C) from mineral soils in 1990 and 2007, respectively. Drainage of organic soils for grazing management led to losses varying from 0.5 to 0.9 Tg CO_2 Eq./yr (0.1 to 0.2 Tg C).

The spatial variability in annual CO_2 flux associated with C stock changes in mineral soils is displayed in Figure 7-11 and Figure 7-12. Soil C stock increased in most states for *Land Converted to Grassland*. The largest gains were in the South-Central region, Midwest, and northern Great Plains. The patterns were driven by conversion of annual cropland into continuous pasture. Emissions from organic soils were largest in California, Florida and the upper Midwest, coinciding with largest concentrations of organic soils in the United States that are used for agricultural production.

Methodology

This section includes a brief description of the methodology used to estimate changes in soil C stocks due to agricultural land-use and management activities on mineral soils for *Land Converted to Grassland*. 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 3.13.

Soil C stock changes were estimated for *Land Converted to Grassland* according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2000). 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. However, the NRI program initiated annual data collection in 1998, and the annual data are currently available through 2003. NRI points were classified as *Land Converted to Grassland* in a given year between 1990 and 2007 if the land use was grassland, but had been another use in the previous 20 years. Grassland includes pasture and rangeland used for grass forage production, where the primary use is livestock grazing. Rangeland typically includes extensive areas of

Table 7-34: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg CO_2 Eq.)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils[a]	(22.7)	(23.4)	(32.8)	(27.6)	(27.6)	(27.6)
Organic Soils	0.5	0.9	0.9	0.9	0.9	0.9
Total Net Flux	**(22.3)**	**(22.5)**	**(32.0)**	**(26.7)**	**(26.7)**	**(26.7)**

[a] Stock changes due to application of sewage sludge are reported in *Grassland Remaining Grassland*.
Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

Table 7-35: Net CO_2 Flux from Soil C Stock Changes for *Land Converted to Grassland* (Tg C)

Soil Type	1990	1995	2000	2005	2006	2007
Mineral Soils[a]	(6.2)	(6.4)	(9.0)	(7.5)	(7.5)	(7.5)
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2
Total Net Flux	**(6.1)**	**(6.1)**	**(8.7)**	**(7.3)**	**(7.3)**	**(7.3)**

[a] Stock changes due to application of sewage sludge are reported in *Grassland Remaining Grassland*.
Note: Parentheses indicate net sequestration. Shaded areas indicate values based on a combination of historical data and projections. All other values are based on historical data only. Totals may not sum due to independent rounding.

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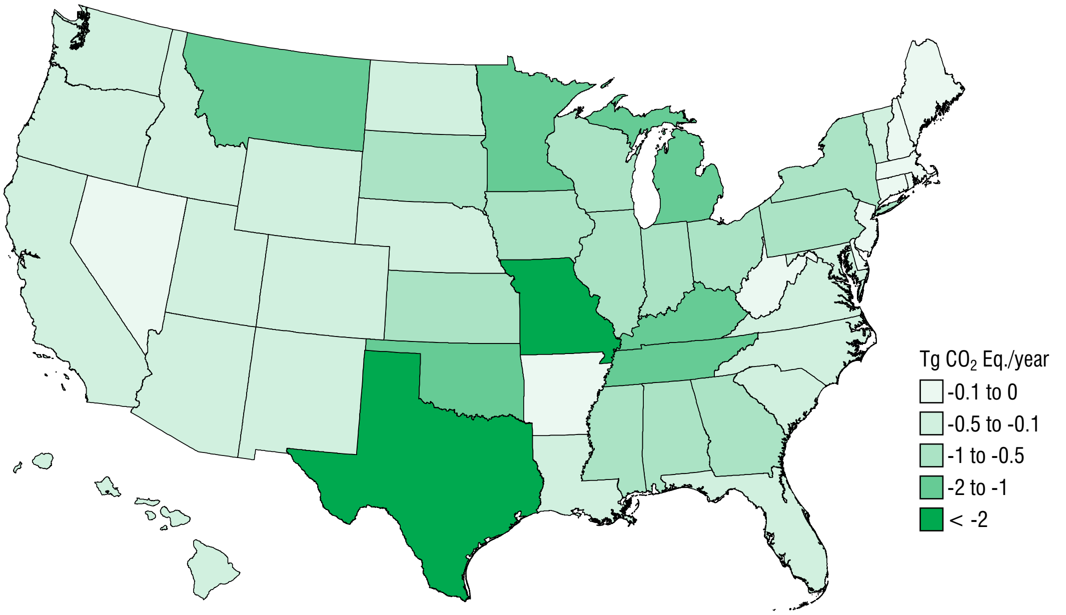
[46] CO_2 emissions associated with liming are also estimated but included in a separate section of the report.

Figure 7-11

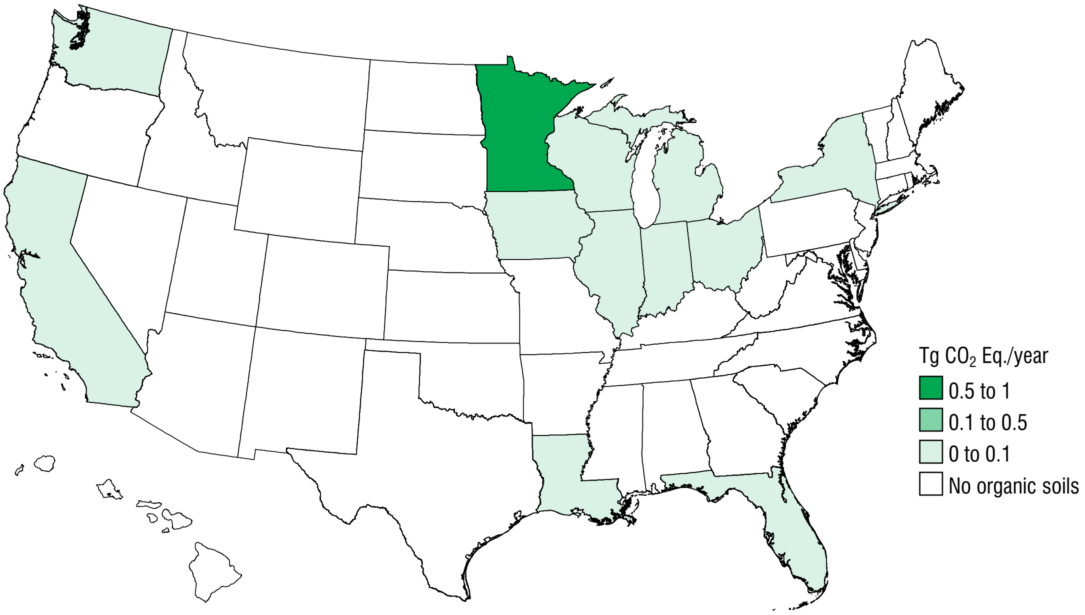
Total Net Annual CO_2 Flux For Mineral Soils Under Agricultural Management within States, 2007, *Land Converted to Grassland*



Note: Values greater than zero represent emissions, and values less than zero represent sequestration. Map accounts for fluxes associated with the Tier 2 and 3 inventory computations. See Methodology for additional details.

Figure 7-12

Total Net Annual CO_2 Flux For Organic Soils Under Agricultural Management within States, 2007, *Land Converted to Grassland*



Note: Values greater than zero represent emissions.

native grassland that are not intensively managed, while pastures are often seeded grassland, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach was used to estimate C stock changes for *Land Converted to Grassland* on most mineral soils. C stock changes on the remaining soils were estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, perennial/horticultural crops, and rice; land areas with very gravelly, cobbly or shaley soils (greater than 35 percent by volume); and land converted from forest or federal ownership.[47] A Tier 2 approach was also used to estimate additional changes in mineral soil C stocks due to sewage sludge amendments. However, stock changes associated with sewage sludge amendments are reported in the *Grassland Remaining Grassland* section.

Tier 3 Approach

Mineral SOC stocks and stock changes were estimated using the Century biogeochemical model as described for *Grassland Remaining Grassland*. Historical land-use and management patterns were used in the Century simulations as recorded in the NRI survey, with supplemental information on fertilizer use and rates from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) and the National Agricultural Statistics Service (NASS 1992, 1999, 2004) (see *Grassland Remaining Grassland* Tier 3 methods section for additional information).

Tier 2 Approach

The Tier 2 approach used for *Land Converted to Grassland* on mineral soils is the same as described for *Cropland Remaining Cropland* (See *Cropland Remaining Cropland* Tier 2 Approach and Annex 3.13 for additional information).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* were estimated using the Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Emissions were based on the 1992 and 1997 *Land Converted to Grassland* areas from the 1997 *National Resources Inventory* (USDA-NRCS 2000). The annual flux estimated for 1992 was applied to 1990 through 1992, and the annual flux estimated for 1997 was applied to 1993 through 2007.

Uncertainty

Uncertainty analysis for mineral soil C stock changes using the Tier 3 and Tier 2 approaches were based on the same method described in *Cropland Remaining Cropland*, except that the uncertainty inherent in the structure of the Century model was not addressed. The uncertainty or annual C emission estimates from drained organic soils in *Land Converted to Grassland* was estimated using the Tier 2 approach, as described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 7-36 for each subsource (i.e., mineral soil C stocks and organic soil C stocks), disaggregated to the level of the inventory methodology employed (i.e., Tier 2 and Tier 3). Uncertainty for the portions of the Inventory estimated with Tier 2 and 3 approaches was derived using a Monte Carlo approach (see Annex 3.13 for further discussion). A combined uncertainty estimate for changes in agricultural soil C stocks is also included. Uncertainty estimates from each component were combined using the error propagation equation in accordance with 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 *Land Converted to Grassland* ranged from 8 percent below to 9 percent above the 2007 estimate of -26.7 Tg CO_2 Eq.

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[47] Federal land is not a land use, but rather an ownership designation that is treated as forest or nominal grassland for purposes of these calculations. The specific use for federal lands is not identified in the NRI survey (USDA-NRCS 2000).

Table 7-36: Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Land Converted to Grassland* (Tg CO_2 Eq. and Percent)

Source	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Land Converted to Grassland, Tier 3 Inventory Methodology	(22.6)	(23.1)	(22.1)	-2%	+2%
Mineral Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	(5.0)	(7.0)	(2.8)	-39%	+43%
Organic Soil C Stocks: Land Converted to Grassland, Tier 2 Inventory Methodology	0.9	0.2	1.8	-76%	+104%
Combined Uncertainty for Flux Associated with Agricultural Soil Carbon Stocks in Land Converted to Grassland	**(26.7)**	**(28.8)**	**(24.3)**	**-8%**	**+9%**

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

QA/QC and Verification

See the QA/QC and Verification section under *Grassland Remaining Grassland*.

Recalculations Discussion

Annual survey data from the USDA *National Resources Inventory* (NRI) were incorporated into this year's Inventory. This resulted in several changes to the inventory methods:

First, the availability of new data extended the time series of activity data beyond 1997 to 2003.[48] In previous Inventories, activity data were only available through 1997, and so subsequent years were treated as the same land use practice occurring in 1997.

Second, annual area data, rather than area data that had been collected in 5-year increments, were used to estimate soil C stock changes, leading to more accurate estimates.

Third, each NRI point was simulated separately, instead of simulating clusters of points that had common land use histories and edaphic characteristics in a county.

Fourth, NRI area data were reconciled with the forest area estimates in the Forest Inventory and Analysis (FIA) dataset, and were incorporated into the estimation of soil C stock changes. The reconciliation led to adjustments in the grassland areas in the NRI dataset, including *Land Converted to Grassland*.[49]

Overall, the recalculations resulted in an average annual increase in soil C stocks of 9.4 Tg CO_2 Eq. for the time series from 1990 through 2006, compared to the previous Inventory.

Planned Improvements

The empirically-based uncertainty estimator described in the *Cropland Remaining Cropland* section for the Tier 3 approach has not been developed to estimate uncertainties in Century model results for *Land Converted to Grassland*, but this is a planned improvement for the Inventory. This improvement will produce a more rigorous assessment of uncertainty. See Planned Improvements section under *Cropland Remaining Cropland* for additional planned improvements.

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[48] Note that the new NRI data were only used in the Tier 3 inventory. The Tier 2 portion of the inventory still used data from the 1997 *National Resources Inventory*, but will be updated in the future.

[49] NRI area data for forest lands was adjusted the match the forest area estimates in the Forest Inventory and Analysis dataset. In order to maintain the same total area, the area data for grasslands and wetlands in the NRI were adjusted to offset the increase or decrease in the forest land area (see section on Representation of U.S. Land Base for more information).

7.8. Wetlands Remaining Wetlands (IPCC Source Category 5D1)

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., draining, and clearing surface biomass); extraction (which results in the emissions reported under *Peatlands Remaining Peatlands*); and abandonment, restoration or conversion of the land to another use.

CO_2 emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al., 2004); however, methane emissions are assumed to be insignificant under Tier 1 IPCC (2006) methods. N_2O emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release GHG emissions, and at present no methodology is provided by IPCC (2006) to estimate GHG emissions or removals from restored peatlands. This Inventory estimates both CO_2 and N_2O emissions from lands undergoing peat extraction in accordance with Tier 1 IPCC (2006) guidelines.

CO_2 and N_2O Emissions from Lands Undergoing Peat Extraction

IPCC (2006) recommends reporting CO_2 and N_2O emissions from lands undergoing peat extraction (i.e., *Peatlands Remaining Peatlands*) as part of the estimate for emissions from managed wetlands. Peatlands occur in wetland areas 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 the course of many 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 and wetlands in states further south. 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 but nutrient-rich.

IPCC (2006) recommends considering both on-site and off-site emissions when estimating CO_2 emissions from lands undergoing peat extraction using the Tier 1 approach. Current methodologies estimate only on-site N_2O emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat. On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. On-site N_2O is emitted during draining depending on site fertility and if the deposit contains significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O.

Off-site CO_2 emissions from managed peatlands occur from the horticultural and landscaping use of peat. CO_2 emissions occur as the nutrient-poor (but now fertilizer-enriched) peat is used in bedding plants, other greenhouse and plant nursery production, and by consumers, and as nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominately for horticultural purposes. The magnitude of the CO_2 emitted from peat depends on whether the peat has been extracted from nutrient-rich or nutrient-poor peat deposits.

Total emissions from lands undergoing peat extraction have fluctuated between 0.9 and 1.2 Tg CO_2 Eq. across the time series with a gentle decrease until 1996 followed by an increase though 2000. Since 2000, total emissions have decreased with some fluctuations. Carbon dioxide emissions from lands undergoing peat extraction have fluctuated

Table 7-37: Emissions from Lands Undergoing Peat Extraction (Tg CO_2 Eq.)

Gas	1990	1995	2000	2005	2006	2007
CO_2	1.0	1.0	1.2	1.1	0.9	1.0
N_2O	+	+	+	+	+	+
Total	**1.0**	**1.0**	**1.2**	**1.1**	**0.9**	**1.0**

+ Does not exceed 0.05 Tg CO_2 Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports and stockpiles (i.e., apparent consumption).

Table 7-38: Emissions from Lands Undergoing Peat Extraction (Gg)

Gas	1990	1995	2000	2005	2006	2007
CO_2	1,033	1,018	1,227	1,079	879	1,010
N_2O	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports and stockpiles (i.e., apparent consumption).

between 0.9 and 1.2 Tg CO_2 Eq. in recent years and have driven the trends in total emissions. Nitrous oxide emissions remained close to zero in recent years, with a decreasing trend until 1995 followed by an overall increase with fluctuations until around 2000. Since 2000, N_2O emissions have fluctuated but shown an overall decrease. (See Table 7-37 and Table 7-38).

Methodology

Off-site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from lands undergoing peat extraction were calculated by apportioning the annual weight of peat produced in the United States (Table 7-39) 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 carbon fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. 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 Industry Surveys* from the U.S. Geological Survey (USGS 1990 through 2008). 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. The USGS often receives a response to the survey from most of the smaller peat producers, but fewer of the larger ones. For example, of the four active operations producing 23,000 or more metric tons per year, two did not respond to the survey in 2007. As a result, the USGS estimates production from the nonrespondent peat producers based on responses to previous surveys (responses from 2004 and 2005, in the case above) or other sources. Estimates were made separately for Alaska, because the state conducts its own mineral survey and reports peat production

Table 7-39: Peat Production of Lower 48 States (in thousands of Metric Tons)

Type of Deposit	1990	1995	2000	2005	2006	2007
Nutrient-Rich	595.1	531.4	728.6	657.6	529.0	581.0
Nutrient-Poor	55.4	116.6	63.4	27.4	22.0	54.0
Total Production	**692.0**	**648.0**	**792.0**	**685.0**	**551.0**	**635.0**

Source: USGS (1990–2008) *Minerals Yearbook* and *Mineral Industry Surveys*.

Table 7-40: Peat Production of Alaska (in thousands of Cubic Meters)

	1990	1995	2000	2005	2006	2007
Total Production	49.7	26.8	27.2	47.8	50.8	51.0

Source: Szumigala, D.J. and R.A. Hughes (1990–2007) *Alaska's Mineral Industry Reports*. Alaska Department of Natural Resources.

by volume, rather than by weight (Table 7-40). However, volume production data was used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific carbon fraction conversion factors from IPCC (2006).[50]

The apparent consumption of peat in the United States, which includes production plus imports minus exports plus the decrease in stockpiles, is over two-and-a-half times the amount of domestic peat production. Therefore, off-site CO_2 emissions from the use of all horticultural peat within the United States are not accounted for using the Tier 1 approach. The United States has increasingly imported peat from Canada for horticultural purposes; in 2007, imports of sphagnum moss (nutrient-poor) peat from Canada represented 97 percent of total U.S. peat imports (USGS 2008). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emissions 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 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[51] can extract up to 100 metric tons per hectare per year (Cleary 2005). The area of land managed for peat extraction in the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year. The annual land area estimates were then multiplied by the appropriate nutrient-rich or nutrient-poor IPCC (2006) default emission factor in order to calculate on-site CO_2 emission estimates. Production data is not available by weight for Alaska. In order to calculate on-site emissions resulting from land undergoing peat extraction in Alaska, the production data by volume were converted to weight using annual peat density values, and then converted to land area estimates using the 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 carbon 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. Since vacuum-harvested peatlands have an average lifespan of thirty-five years (Cleary 2005), it seems reasonable to assume that no new areas are being cleared of vegetation for peat extraction. Other changes in carbon stocks in living biomass on managed peat lands are also assumed to be zero under the Tier 1 methodology (IPCC 2006).

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emissions estimates on the area of nutrient-rich peatlands managed for peat extraction. These data are not available for the United States, but the on-site CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O emissions, the

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[50] 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).

[51] 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).

area of nutrient rich land undergoing peat extraction was multiplied by the appropriate default emission factor taken from IPCC (2006).

Uncertainty

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. This same uncertainty and distribution was assumed for the peat type production percentages. The uncertainty associated with the Alaskan reported production data was assumed to be the same as the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the Alaskan Department of Natural Resources estimate 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. The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008). IPCC (2006) gives uncertainty values for the emission 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 carbon fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed. Based on these values and distributions, a Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of CO_2 and N_2O emissions from land undergoing peat extraction. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-41. CO_2 emissions from lands undergoing peat extraction in 2007 were estimated to be between 0.70 and 1.30 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 31 percent below to 29 percent above the 2007 emission estimate of 0.99 Tg CO_2 Eq. N_2O emissions from lands undergoing peat extraction in 2007 were estimated to be between 0.001 and 0.007 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of 73 percent below to 37 percent above the 2007 emission estimate of 0.005 Tg CO_2 Eq.

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

This is the first year that emissions from Lands Undergoing Peat Extraction are included in the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Planned Improvements

In order to further improve estimates of CO_2 and N_2O emissions from lands undergoing peat extraction, future efforts will consider options for obtaining better data on the quantity of peat harvested per hectare and the total area undergoing peat extraction.

Table 7-41: Tier-2 Quantitative Uncertainty Estimates for CO_2 and N_2O Emissions from Lands Undergoing Peat Extraction

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lands Undergoing Peat Extraction	CO_2	1.0	0.7	1.3	-31%	+29%
Lands Undergoing Peat Extraction	N_2O	+	+	+	-73%	+37%

+ Does not exceed 0.05 Tg CO_2 Eq.

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

7.9. Settlements Remaining Settlements

Changes in Carbon Stocks in Urban Trees (IPCC Source Category 5E1)

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 4.4 percent of the United States (Nowak et al. 2005). With an average tree canopy cover of 27 percent, urban areas account for approximately 3 percent of total tree cover in the continental United States (Nowak et al. 2001). Trees in urban areas of the United States were estimated to account for an average annual net sequestration of 79.1 Tg CO_2 Eq. (22 Tg C) over the period from 1990 through 2007. Total sequestration increased by 61 percent between 1990 and 2007 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. Annual estimates of CO_2 flux were developed based on periodic (1990 and 2000) U.S. Census data on urban area (Table 7-42). Net C flux from urban trees in 2007 was estimated to be -97.6 Tg CO_2 Eq. (-26.6 Tg C).

Net C flux from urban trees is proportionately greater on an area basis than that of forests. This trend is primarily the result of different net growth rates in urban areas versus forests—urban trees often grow faster than forest trees because of the relatively open structure of the urban forest (Nowak and Crane 2002). Also, areas in each case are accounted for differently. Because urban areas contain less tree coverage than forest areas, the C storage per hectare of land is in fact smaller for urban areas. However, urban tree reporting occurs on a per unit tree cover basis (tree canopy area), rather than total land area. Urban trees, therefore, appear to have a greater C density than forested areas (Nowak and Crane 2002).

Table 7-42: Net C Flux from Urban Trees (Tg CO_2 Eq. and Tg C)

Year	Tg CO_2 Eq.	Tg C
1990	(60.6)	(16.5)
1995	(71.5)	(19.5)
2000	(82.4)	(22.5)
2005	(93.3)	(25.4)
2006	(95.5)	(26.0)
2007	(97.6)	(26.6)

Note: Parentheses indicate net sequestration.

Methodology

The methodology used by Nowak and Crane (2002) is based on average annual estimates of urban tree growth and decomposition, which were derived from field measurements and data from the scientific literature, urban area estimates from U.S. Census data, and urban tree cover estimates from remote sensing data. This approach is consistent with the default IPCC methodology in IPCC (2006), although sufficient data are not yet available to determine interannual gains and losses in C stocks in the living biomass of urban trees. Annual changes in net C flux from urban trees are based solely on changes in total urban area in the United States.

Most of the field data were analyzed using the U.S. Forest Service's Urban Forest Effects (UFORE) model.[52] The UFORE model 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 (Nowak et al. 2007a).

Nowak and Crane (2002) developed estimates of annual gross C sequestration from tree growth and annual gross C emissions from decomposition for 10 U.S. cities. Subsequent studies have developed estimates for 5 more cities, resulting in estimates for the following 15 cities: Atlanta, GA; Baltimore, MD; Boston, MA; Chicago, IL; Freehold, NJ; Jersey City, NJ; Minneapolis, MN; Moorestown, NJ; New York, NY; Oakland, CA; Philadelphia, PA; San Francisco, CA; Syracuse, NY; Washington, DC; and Woodbridge, NJ. Field data was collected for a sample of trees in each of the 15 cities during the period from 1989 through 2006,

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[52] Oakland and Chicago estimates were based on prototypes to the UFORE model.

including tree measurements of stem diameter, tree height, crown height, and crown width, and information on location, species, and canopy condition. The data for each tree was 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 contents, a C content of 50 percent (dry weight basis), and an adjustment factor to account for urban trees having less aboveground biomass than predicted by allometric equations based on forest trees. Carbon storage estimates for deciduous trees were structured to include only carbon stored in wood. These calculations were then used to form an estimation equation for each species of tree, encompassing a range of diameters.

Tree growth was estimated using annual height growth and diameter growth rates for specific land uses and diameter classes. 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 carbon storage estimates between year 1 and year x + 1 gave the gross amount of C sequestered. These annual gross C sequestration rates for each species (or genus), diameter class, and land-use condition (parks, transportation, vacant, golf courses, etc.) were then scaled up to city estimates using tree population information.

Gross C emissions result from tree death and removals. These emissions 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 field data from the 15 cities, some of which are unpublished (Nowak 2007c), are described in Nowak and Crane (2002), Nowak et al. (2007a), and references cited therein. The allometric equations applied to the field data for each tree were taken from the scientific literature (see Nowak 1994, 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). A root-to-shoot ratio of 0.26 was taken from Cairns et al. (1997), and species- or genus-specific moisture contents were taken from various literature sources (see Nowak 1994). Tree growth rates were taken from existing literature. Average diameter growth was based on the following sources: estimates for trees in forest stands came from Smith and Shifley (1984); estimates for trees on land uses with a park-like structure came from deVries (1987); and estimates for more open-grown trees came from Nowak (1994). Formulas from Fleming (1988) formed the basis for average height growth calculations. Growth rates were adjusted to account for tree condition. Growth factors for Atlanta, Boston, Chicago, Freehold, Jersey City, Moorestown, New York, Oakland, Philadelphia, and Woodbridge were adjusted based on the typical growth conditions of different land-use categories (e.g., forest stands, park-like stands). Growth factors for the more recent studies in Baltimore, Minneapolis, San Francisco, Syracuse, and Washington were adjusted using an updated methodology based on the condition of each individual tree, which is determined using tree competition factors (depending on whether it is open grown or suppressed) (Nowak 2007b). 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 and Crane 2002).

National annual net C sequestration by urban trees was calculated based on estimates of gross and net sequestration from 13 of the 15 cities (Table 7-43), and urban area and urban tree cover data for the United States. Annual net C sequestration estimates[53] were derived for 13 cities by subtracting the annual gross emission estimates from the annual gross sequestration estimates. The urban area estimates were based on 1990 and 2000 U.S. Census data.

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[53] Net estimates were not available for two cities (Chicago and Oakland).

Table 7-43: C Stocks (Metric Tons C), Annual C Sequestration (Metric Tons C/yr), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2 cover-yr) for 15 U.S. Cities

City	Carbon Stocks	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover
Atlanta, GA	1,219,256	42,093	32,169	36.7%	0.34	0.26
Baltimore, MD	541,589	14,696	9,261	21.0%	0.35	0.22
Boston, MA	289,392	9,525	6,966	22.3%	0.30	0.22
Chicago, IL	NA	NA	NA	11.0%	0.61	NA
Freehold, NJ	18,144	494	318	34.4%	0.28	0.18
Jersey City, NJ	19,051	807	577	11.5%	0.18	0.13
Minneapolis, MN	226,796	8,074	4,265	26.4%	0.20	0.11
Moorestown, NJ	106,141	3,411	2,577	28.0%	0.32	0.24
New York, NY	1,224,699	38,374	20,786	20.9%	0.23	0.12
Oakland, CA	NA	NA	NA	21.0%	NA	NA
Philadelphia, PA	480,808	14,606	10,530	15.7%	0.27	0.20
San Francisco, CA	175,994	4,627	4,152	11.9%	0.33	0.29
Syracuse, NY	156,943	4,917	4,270	23.1%	0.33	0.29
Washington, DC	477,179	14,696	11,661	28.6%	0.32	0.26
Woodbridge, NJ	145,150	5,044	3,663	29.5%	0.28	0.21

NA = not analyzed.
Sources: Nowak and Crane (2002) and Nowak (2007a,c).

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. Urban land area has increased by approximately 36 percent from 1990 to 2000; Nowak et al. (2005) estimate that the changes in the definition of urban land have resulted in approximately 20 percent of the total reported increase in urban land area from 1990 to 2000. Under both 1990 and 2000 definitions, urban encompasses most cities, towns, and villages (i.e., it includes both urban and suburban areas). The gross and net C sequestration values for each city were divided by each city's area of tree cover to determine the average annual sequestration rates per unit of tree area for each city. The median value for gross sequestration (0.31 kg C/m^2-year) was then multiplied by the estimate of national urban tree cover area to estimate national annual gross sequestration. To estimate national annual net sequestration, the estimate of national annual gross sequestration was multiplied by the average of the ratios of net to gross sequestration for those cities that had both estimates (0.72). The urban tree cover estimates for each of the 15 cities and the United States were obtained from Dwyer et al. (2000), Nowak et al. (2002), and Nowak (2007a). The urban area estimates were taken from Nowak et al. (2005).

Uncertainty

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 13 of the 15 U.S. cities. A 10 percent uncertainty was associated with urban area estimates while a 5 percent uncertainty was associated with percent urban tree coverage. Both of these uncertainty estimates were based on expert judgment. Uncertainty associated with estimates of gross and net C sequestration for 13 of the 15 U.S. cities was based on standard error estimates for each of the city-level sequestration estimates reported by Nowak (2007c). These estimates are based on field data collected in 13 of the 15 U.S. cities, 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

Table 7-44: Tier 2 Quantitative Uncertainty Estimates for Net C Flux from Changes in C Stocks in Urban Trees (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Urban Trees	CO_2	(97.6)	(115.3)	(77.3)	-18%	+21%

Note: Parentheses indicate net sequestration.

(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 at the beginning of this chapter.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-44. The net C flux from changes in C stocks in urban trees in 2007 was estimated to be between -115.3 and -77.3 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 18 percent below and 21 percent above the 2007 flux estimate of -97.6 Tg CO_2 Eq.

QA/QC and Verification

The net C flux resulting from urban trees was calculated using estimates of gross and net C sequestration for urban trees and urban tree coverage area found in literature. The validity of these data for their use in this section of the Inventory was evaluated through correspondence established with an author of the papers. Through this correspondence, the methods used to collect the urban tree sequestration and area data were further clarified and the use of these data in the Inventory was reviewed and validated (Nowak 2002a, 2007b).

Planned Improvements

A consistent representation of the managed land base in the United States is being developed. A component of this effort, which is discussed at the beginning of the LULUCF chapter, will involve reconciling the overlap between urban forest and non-urban forest greenhouse gas inventories. It is highly likely that urban forest inventories are including areas considered non-urban under the Forest Inventory and Analysis (FIA) program of the USDA Forest Service, resulting in "double-counting" of these land areas in estimates of C stocks and fluxes for the Inventory. Planned improvements to the FIA program include the development of a long-term dataset that will define urban area boundaries and make it possible to identify what area is forested. Once those data become available, they will be incorporated into estimates of net C flux resulting from urban trees.

Urban forest data for additional cities is expected in the near future, and the use of this data will further refine the estimated median sequestration value. It may also be possible to report C losses and gains separately in the future. It is currently not possible, since existing studies estimate rather than measure natality or mortality; net sequestration estimates are based on assumptions about whether dead trees are being removed, burned, or chipped. There is an effort underway to develop long-term data on permanent plots in at least two cities, which would allow for direct calculation of C losses and gains from observed rather than estimated natality and mortality of trees.

Direct N_2O Fluxes from Settlement Soils (IPCC Source Category 5E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 2.5 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 N_2O emissions per unit area. In addition to synthetic N fertilizers, a portion of surface-applied sewage sludge is applied to settlement areas. In 2007, N_2O emissions from this source were 1.6 Tg CO_2 Eq. (5.2 Gg). There was an overall increase of 61 percent over the period from 1990 through 2007 due to a general

Table 7-45: N_2O Fluxes from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Gg N_2O)

Year	Tg CO_2 Eq.	Gg
1990	1.0	3.2
1995	1.2	4.0
2000	1.2	3.9
2005	1.5	4.9
2006	1.5	5.0
2007	1.6	5.2

Note: These estimates include direct N_2O emissions from N fertilizer additions only. Indirect N_2O emissions from fertilizer additions are reported in the Agriculture chapter. These estimates include emissions from both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

increase in the application of synthetic N fertilizers to an expanding settlement area. 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 7-45.

Methodology

For soils within *Settlements Remaining Settlements*, the IPCC Tier 1 approach was used to estimate soil N_2O emissions from synthetic N fertilizer and sewage sludge additions. Estimates of direct N_2O emissions from soils in settlements were 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 in surface disposal of sewage sludge (see Annex 3.11 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 based on sales records at the county level from 1982 through 2001 (Ruddy et al. 2006). Non-farm N fertilizer was assumed to be applied to settlements and forests and values for 2002 through 2007 were based on 2001 values adjusted for annual total N fertilizer sales in the United States. Settlement application was calculated by subtracting forest application from total non-farm fertilizer use. Sewage sludge applications were derived from national data on sewage sludge generation, disposition, and N content (see Annex 3.11 for further detail).

The total amount of N resulting from these sources was multiplied by the IPCC default emission factor for applied N (1 percent) to estimate direct N_2O emissions (IPCC 2006). The volatilized and leached/runoff proportions, calculated with the IPCC default volatilization factors (10 or 20 percent, respectively, for synthetic or organic N fertilizers) and leaching/runoff factor for wet areas (30 percent), were included with the total N contributions to indirect emissions, as reported in the Agricultural Soil Management source category of the Agriculture chapter.

Uncertainty

The amount of N_2O emitted from settlements depends not only on N inputs, 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 N_2O flux is complex and highly uncertain. The IPCC default methodology does not incorporate any of these variables and only accounts for 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 was assigned a default level[54] of ±50 percent. Uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was 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. Uncertainty in the emission factors was provided by the IPCC (2006).

Quantitative uncertainty of this source category was estimated through the IPCC-recommended Tier 2 uncertainty estimation methodology. The uncertainty ranges around the 2005 activity data and emission factor input variables were directly applied to the 2007 emission estimates. The results of the quantitative uncertainty analysis are summarized in Table 7-46. N_2O emissions from soils in *Settlements Remaining Settlements* in 2007 were estimated to be between 0.8 and 4.2

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[54] No uncertainty is provided with the USGS application data (Ruddy et al. 2006) so a conservative ±50% was used in the analysis.

Table 7-46: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emissions (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements: N_2O Fluxes from Soils	N_2O	1.6	0.8	4.2	-49%	+163%

Note: This estimate includes direct N_2O emissions from N fertilizer additions to both *Settlements Remaining Settlements* and from *Land Converted to Settlements*.

Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 49 percent below to 163 percent above the 2007 emission estimate of 1.6 Tg CO_2 Eq.

Recalculations Discussion

The total amount of fertilizer in non-agricultural uses has been estimated by the USGS for 1990 through 2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). In previous Inventories, data for 2001 was used for subsequent years without adjustment. For subsequent years in the current Inventory (2002 though 2007), county-level data on non-farm fertilizer use for 2001 were adjusted based on annual fluctuations in total U.S. fertilizer sales. This change resulted in a small (less than 1 percent on average) increase in emissions relative to the previous Inventory.

Planned Improvements

A minor improvement is to update the uncertainty analysis for direct emissions from settlements to be consistent with the most recent activity data for this source.

7.10. Land Converted to Settlements (Source Category 5E2)

Land-use change is constantly occurring, and land under a number of uses undergoes urbanization in the United States each year. However, data on the amount of land converted to settlements is currently lacking. Given the lack of available information relevant to this particular IPCC source category, it is not possible to separate CO_2 or N_2O fluxes on *Land Converted to Settlements* from fluxes on *Settlements Remaining Settlements* at this time.

7.11. Other (IPCC Source Category 5G)

Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills

In the United States, a significant change in C stocks results from the removal of yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps from settlements to be disposed in landfills. Yard trimmings 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 discarded in landfills. Carbon 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 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 therefore 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 50 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 2008; Schneider 2007, 2008). 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 7 percent decrease in the tonnage generated (i.e., collected for composting or disposal). At the same time, a dramatic 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 29 percent in 2007. The net effect of the reduction in generation and the increase in composting is a 62 percent decrease in the quantity of yard trimmings disposed in landfills since 1990.

Food scraps generation has grown by 52 percent since 1990, but the proportion of food scraps discarded in landfills has decreased slightly from 81 percent in 1990 to 79 percent in 2007. Overall, the decrease in the yard trimmings landfill disposal rate has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual landfill carbon storage from 23.5 Tg CO_2 Eq. in 1990 to 9.8 Tg CO_2 Eq. in 2007 (Table 7-47 and Table 7-48).

Methodology

When wastes of sustainable, 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 global C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008), and thus the stock of carbon in landfills can increase, with the net effect being a net atmospheric removal of carbon. 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 portion of C 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

Table 7-47: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg CO_2 Eq.)

Carbon Pool	1990	1995	2000	2005	2006	2007
Yard Trimmings	**(21.2)**	**(12.5)**	**(8.2)**	**(6.6)**	**(6.8)**	**(6.3)**
Grass	(1.9)	(0.8)	(0.4)	(0.4)	(0.5)	(0.4)
Leaves	(9.7)	(6.0)	(4.0)	(3.3)	(3.3)	(3.1)
Branches	(9.7)	(5.8)	(3.7)	(3.0)	(3.0)	(2.8)
Food Scraps	**(2.2)**	**(1.4)**	**(3.1)**	**(3.5)**	**(3.6)**	**(3.5)**
Total Net Flux	**(23.5)**	**(13.9)**	**(11.3)**	**(10.2)**	**(10.4)**	**(9.8)**

Note: Totals may not sum due to independent rounding.

Table 7-48: Net Changes in Yard Trimming and Food Scrap Stocks in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2005	2006	2007
Yard Trimmings	**(5.8)**	**(3.4)**	**(2.2)**	**(1.8)**	**(1.8)**	**(1.7)**
Grass	(0.5)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Leaves	(2.7)	(1.6)	(1.1)	(0.9)	(0.9)	(0.8)
Branches	(2.6)	(1.6)	(1.0)	(0.8)	(0.8)	(0.8)
Food Scraps	**(0.6)**	**(0.4)**	**(0.9)**	**(1.0)**	**(1.0)**	**(0.9)**
Total Net Flux	**(6.4)**	**(3.8)**	**(3.1)**	**(2.8)**	**(2.8)**	**(2.7)**

Note: Totals may not sum due to independent rounding.

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 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 *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2007 Facts and Figures* (EPA 2008), which provides data for 1960, 1970, 1980, 1990, 2000, 2002, and 2004 through 2007. To provide data for some of the missing years, detailed backup data was obtained from Schneider (2007, 2008). Remaining years in the time series for which data were not provided were estimated using linear interpolation. The EPA (2008) report does not subdivide discards of individual materials into volumes landfilled and combusted, although it provides an estimate of the proportion of overall waste stream discards managed in landfills and combustors (i.e., ranging from 92 percent and 8 percent respectively in 1984–86, to 67 percent and 33 percent in 1960).

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 7-49).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with a "seed" containing 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 initial C (shown in the row labeled "CS" in Table 7-49).

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, resulting in emissions of CH_4 and CO_2 (the CH_4 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. Food scraps are assumed to have a half-life of 3.7 years; grass is assumed to have a half-life of 5 years; leaves are assumed to have a half-life of 20 years; and branches are assumed to have a half-life of 23.1 years. The half-life of food scraps is consistent with analysis for landfill CH_4 in the Waste chapter.

Table 7-49: Moisture Content (%), C Storage Factor, Proportion of Initial C Sequestered (%), Initial C Content (%), and Half-Life (years) for Landfilled Yard Trimmings and Food Scraps in Landfills

	Yard Trimmings			Food Scraps
Variable	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
CS, proportion of initial C stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Half-life (years)	5	20	23	4

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 the following formula:

$$LFC_{i,t} = \sum_{n} W_{i,n} \times (1 - MC_i) \times ICC_i \times$$
$$\{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t - n)}]\}$$

where,

t = Year for which C stocks are being estimated (year)
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps)
$LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (metric tons)
$W_{i,n}$ = Mass of waste *i* disposed in landfills in year *n* (metric tons, wet weight)
n = Year in which the waste was disposed (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
k = First order rate constant for waste *i*, which is equal to 0.693 divided by the half-life for decomposition ($year^{-1}$)

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 as the change in stock compared to the preceding year:

$$F_t = TLFC_t - TLFC_{t-1}$$

Thus, the C placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period (2007). 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 1964, more than half of the degradable portion (500,000 metric tons) decomposes, leaving a total of 635,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2007, the total food scraps C originally disposed in 1960 had declined to 179,000 metric tons (i.e., virtually all of the degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed in subsequent years (1961 through 2007), the total landfill C from food scraps in 2007 was 30.6 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 2007, yielding a value of 240.4 million metric tons (as shown in Table 7-50). 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 7-48) is the difference in the landfill C stock for that year and the stock in the preceding year. For example, the net change in 2007 shown in Table 7-48 (2.7 Tg C) is equal to the stock in 2007 (240.4 Tg C) minus the stock in 2006 (237.7 Tg C).

The C stocks calculated through this procedure are shown in Table 7-50.

Uncertainty

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, decomposition rate (half-life), 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).

Table 7-50: C Stocks in Yard Trimmings and Food Scraps in Landfills (Tg C)

Carbon Pool	1990	1995	2000	2005	2006	2007
Yard Trimmings	**160.3**	**183.5**	**196.0**	**206.2**	**208.0**	**209.7**
Grass	16.2	18.0	18.6	19.2	19.4	19.5
Leaves	71.7	82.5	88.6	93.6	94.5	95.3
Branches	72.5	83.1	88.8	93.4	94.2	94.9
Food Scraps	**18.4**	**20.9**	**24.3**	**28.7**	**29.7**	**30.6**
Total Carbon Stocks	**178.7**	**204.4**	**220.3**	**234.9**	**237.7**	**240.4**

Note: Totals may not sum due to independent rounding.

Table 7-51: Tier 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Flux Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(9.8)	(17.9)	(5.5)	-84%	+44%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
Note: Parentheses indicate net sequestration.

There are respective uncertainties associated with each of these factors.

A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 7-51. Total yard trimmings and food scraps CO_2 flux in 2007 was estimated to be between -17.9 and -5.5 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo stochastic simulations). This indicates a range of 84 percent below to 44 percent above the 2007 flux estimate of -9.8 Tg CO_2 Eq. More information on the uncertainty estimates for Yard Trimmings and Food Scraps in Landfills is contained within the Uncertainty Annex.

QA/QC and Verification

A QA/QC analysis was performed for data gathering and input, documentation, and calculation.

Recalculations Discussion

The current Inventory uses updated data from *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: 2007 Facts and Figures* (EPA 2008), which provides updated data through 2007 including revisions to the amount of food scraps generated in 2000 and 2004 through 2007. This update results in 4.6 and 0.5 percent decreases in carbon storage on average across the time series for food scraps and yard trimmings, respectively. This translates to an average 1.0% decrease in carbon storage on average across the time series for the entire source category.

Planned Improvements

Future work is planned to develop improved estimates of the decay rates for the individual materials. Additional analysis may also be performed to evaluate the potential contribution of inorganic C, primarily in the form of carbonates, to landfill sequestration, as well as the consistency between the estimates of C storage described in this chapter and the estimates of landfill CH_4 emissions described in the Waste chapter.

8. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 8-1). Landfills accounted for approximately 23 percent of total U.S. anthropogenic methane (CH_4) emissions in 2007,[1] the second largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and composting of organic waste accounted for approximately 4 percent and less than 1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions from the discharge of wastewater treatment effluents into aquatic environments were estimated, as were N_2O emissions from the treatment process itself. N_2O emissions from composting were also estimated. Together, these waste activities account for approximately 2 percent of total U.S. N_2O emissions. Nitrogen oxide (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 8-1 and Table 8-2.

Overall, in 2007, waste activities generated emissions of 165.6 teragrams of carbon dioxide equivalents (Tg CO_2 Eq.) or just over 2 percent of total U.S. greenhouse gas emissions.

Figure 8-1

2007 Waste Chapter Greenhouse Gas Emission Sources

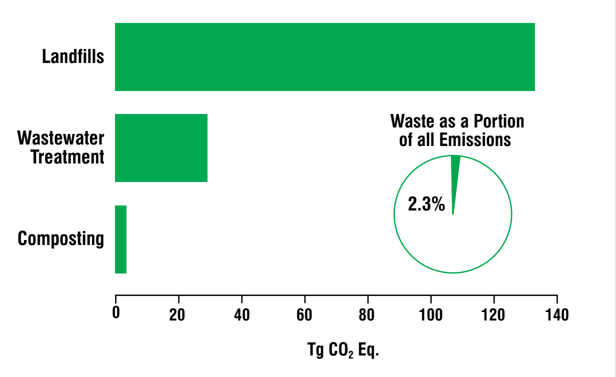

Table 8-1: Emissions from Waste (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**173.0**	**169.9**	**148.8**	**153.8**	**156.5**	**158.9**
Landfills	149.2	144.3	122.3	127.8	130.4	132.9
Wastewater Treatment	23.5	24.8	25.2	24.3	24.5	24.4
Composting	0.3	0.7	1.3	1.6	1.6	1.7
N_2O	**4.0**	**4.8**	**5.8**	**6.5**	**6.6**	**6.7**
Domestic Wastewater Treatment	3.7	4.0	4.5	4.8	4.8	4.9
Composting	0.4	0.8	1.4	1.7	1.8	1.8
Total	**177.1**	**174.7**	**154.6**	**160.2**	**163.0**	**165.6**

Note: Totals may not sum due to independent rounding.

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[1] 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.

Table 8-2: Emissions from Waste (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
CH_4	**8,240**	**8,089**	**7,084**	**7,322**	**7,451**	**7,566**
Landfills	7,105	6,871	5,825	6,088	6,211	6,327
Wastewater Treatment	1,120	1,183	1,200	1,159	1,165	1,160
Composting	15	35	60	75	75	79
N_2O	**13**	**16**	**19**	**21**	**21**	**22**
Domestic Wastewater Treatment	12	13	14	15	15	16
Composting	1	3	4	6	6	6

Note: Totals may not sum due to independent rounding.

8.1. Landfills (IPCC Source Category 6A1)

In 2007, landfill CH_4 emissions were approximately 132.9 Tg CO_2 Eq. (6,327 Gg of CH_4), representing the second largest source of CH_4 emissions in the United States, behind enteric fermentation. Emissions from municipal solid waste (MSW) landfills, which received about 64.5 percent of the total solid waste generated in the United States, accounted for about 90 percent of total landfill emissions, while industrial landfills accounted for the remainder. Approximately 1,800 operational landfills exist in the United States, with the largest landfills receiving most of the waste and generating the majority of the CH_4 (BioCycle 2006, adjusted to include missing data from five states).

After being placed in a landfill, 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 CH_4-producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent carbon dioxide (CO_2) and 50 percent CH_4, by volume.[2] Significant CH_4 production typically begins one or two years after waste disposal in a landfill and continues for 10 to 60 years or longer.

From 1990 to 2007, net CH_4 emissions from landfills decreased by approximately 10 percent (see Table 8-3 and Table 8-4). This net CH_4 emissions decrease is the result of increases in the amount of landfill gas collected and combusted,[3] which has more than offset the additional CH_4 generation resulting from an increase in the amount of municipal solid waste landfilled over the past 17 years. Over the past 6 years, however, the net CH_4 emissions have slowly increased, but have remained relatively steady since 2005. While the amount of landfill gas collected and combusted continues to increase every year, the rate of increase no longer exceeds that rate of additional CH_4 generation resulting from an increase in the amount of municipal solid waste landfilled as the U.S. population grows.

Methane emissions from landfills are a function of several factors, including: (1) the total amount of waste in MSW landfills, which is related to total waste landfilled annually; (2) the characteristics of landfills receiving waste (i.e., composition of waste-in-place, size, climate); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized in landfills instead of being released into the atmosphere. The estimated annual quantity of waste placed in MSW landfills increased from about 209 Tg in 1990 to 291 Tg in 2007, an increase of 28 percent (see Annex 3.14). During this period, the estimated CH_4 recovered and combusted from MSW landfills increased as well. In 1990, for example, approximately 878 Gg of CH_4 were recovered and combusted (i.e., used for energy or flared) from landfills, while in 2007, 5,812 Gg CH_4 was combusted. In 2007, an estimated 59 new landfill gas-to-energy (LFGTE) projects and 55 new flares began operation, resulting

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[2] The percentage of CO_2 in biogas released from a landfill may be smaller because some CO_2 dissolves in landfill water (Bingemer and Crutzen 1987). Additionally, less than 1 percent of landfill gas is typically composed of NMVOCs.

[3] The CO_2 produced from combusted landfill CH_4 at landfills is not counted in national inventories as it is considered part of the natural C cycle of decomposition.

Table 8-3: CH_4 Emissions from Landfills (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
MSW Landfills	172.6	191.8	206.9	241.2	248.1	254.2
Industrial Landfills	11.6	12.9	14.4	15.3	15.3	15.4
Recovered						
Gas-to-Energy	(13.3)	(22.3)	(49.3)	(56.8)	(59.2)	(64.3)
Flared	(5.1)	(22.0)	(36.2)	(57.6)	(59.3)	(57.7)
Oxidized[a]	(16.6)	(16.0)	(13.6)	(14.2)	(14.6)	(14.8)
Total	**149.2**	**144.3**	**122.3**	**127.8**	**130.4**	**132.9**

[a] Includes oxidation at both municipal and industrial landfills.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 8-4: CH_4 Emissions from Landfills (Gg)

Activity	1990	1995	2000	2005	2006	2007
MSW Landfills	8,219	9,132	9,854	11,486	11,813	12,107
Industrial Landfills	554	615	687	728	730	735
Recovered						
Gas-to-Energy	(635)	(1,064)	(2,348)	(2,707)	(2,819)	(3,062)
Flared	(242)	(1,048)	(1,722)	(2,743)	(2,822)	(2,750)
Oxidized[a]	(789)	(763)	(647)	(676)	(690)	(703)
Total	**7,105**	**6,871**	**5,825**	**6,088**	**6,211**	**6,327**

[a] Includes oxidation at both municipal and industrial landfills.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

in a 3 percent increase in the quantity of CH_4 recovered and combusted from 2006 levels.

Over the next several years, the total amount of municipal solid waste generated is expected to increase as the U.S. population continues to grow. The percentage of waste landfilled, however, may decline due to increased recycling and composting practices. In addition, the quantity of CH_4 that is recovered and either flared or used for energy purposes is expected to continue to increase as a result of 1996 federal regulations that require large municipal solid waste 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 encouraging CH_4 recovery and use 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).

Methodology

A detailed description of the methodology used to estimate CH_4 emissions from landfills can be found in Annex 3.14.

CH_4 emissions from landfills were estimated to equal the CH_4 produced from municipal solid waste landfills, plus the CH_4 produced by industrial landfills, minus the CH_4 recovered and combusted, minus the CH_4 oxidized before being released into the atmosphere:

$$CH_{4,\text{Solid Waste}} = [CH_{4,\text{MSW}} + CH_{4,\text{ind}} - R] - Ox$$

where,

$CH_{4,\text{Solid Waste}}$ = CH_4 emissions from solid waste
$CH_{4,\text{MSW}}$ = CH_4 generation from municipal solid waste landfills,
$CH_{4,\text{ind}}$ = CH_4 generation from industrial landfills,
R = CH_4 recovered and combusted, and
Ox = CH_4 oxidized from MSW and industrial landfills before release to the atmosphere.

The methodology for estimating CH_4 emissions from municipal solid waste landfills is based on the first order decay model described by the Intergovernmental Panel on Climate Change (IPCC 2006). Values for the CH_4 generation potential (L_0) and rate constant (k) were obtained from an analysis of CH_4 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 rate constant was found to increase with average annual rainfall; consequently, values of k were developed for 3 ranges of rainfall. The annual quantity of waste placed in landfills was apportioned to the 3 ranges of rainfall based on the percent of the U.S. population in each of the 3 ranges, and historical census data were used to account for the shift in population to more arid areas over time. For further information, see Annex 3.14.

National landfill waste generation and disposal data for 2007 was extrapolated based on BioCycle data and the U.S. Census population from 2006. Data for 1989 through 2006 were obtained from *BioCycle* (2006). Because BioCycle 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 (2007) and national per capita solid waste generation from *BioCycle* (2006). Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's *Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress* (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the first order decay model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For calculations in this Inventory, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in landfills (CH_4 correction factor, or MCF, of 1) and those disposed in dumps (MCF of 0.6). Please see Annex 3.14 for more details.

The estimated landfill gas recovered per year was based on updated data collected from vendors of flaring equipment, a database of landfill gas-to-energy (LFGTE) projects compiled by LMOP (EPA 2008), and a database maintained by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007). As the EIA database only included data through 2006, 2007 recovery for projects included in the EIA database were assumed to be the same as in 2006. The three databases were carefully compared to identify landfills that were in two or all three of the databases to avoid double-counting reductions. Based on the information provided by the EIA and flare vendor databases, the CH_4 combusted by flares in operation from 1990 to 2007 was estimated. This quantity likely underestimates flaring because these databases do not have information on all flares in operation. Additionally, the EIA and LMOP databases provided data on landfill gas flow and energy generation for landfills with LFGTE projects. If a landfill in the EIA database was also in the LMOP and/or the flare vendor database, the emissions avoided were based on the EIA data because landfill owners or operators reported the amount recovered based on measurements of gas flow and concentration, and the reporting accounted for changes over time. If both flare data and LMOP recovery data were available for any of the remaining landfills (i.e., not in the EIA database), then the emissions recovery was based on the LMOP data, which provides reported landfill-specific data on gas flow for direct use projects and project capacity (i.e., megawatts) for electricity projects. The flare data, on the other hand, only provided a range of landfill gas flow for a given flare size. Given that each LFGTE project is likely to also have a flare, double counting reductions from flares and LFGTE projects in the LMOP database was avoided by subtracting emissions reductions associated with LFGTE projects for which a flare had not been identified from the emissions reductions associated with flares.

A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions avoided. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's *AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4* (EPA 1998) efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Emissions from industrial landfills were estimated from activity data for industrial production (ERG 2008), waste disposal factors, and the first order decay model. As over 99 percent of the organic waste placed in industrial landfills originated from the food processing (meat, vegetables, fruits) and pulp and paper industries, estimates of industrial landfill emissions focused on these two sectors (EPA 1993). The amount of CH_4 oxidized by the landfill cover at both municipal and industrial landfills was assumed to be ten percent of the CH_4 generated that is not recovered (IPCC 2006, Mancinelli and McKay 1985, Czepiel et al. 1996). To calculate net CH_4 emissions, both CH_4 recovered and CH_4 oxidized were subtracted from CH_4 generated at municipal and industrial landfills.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from landfills. The primary uncertainty concerns the characterization of landfills. Information is not available on two fundamental factors affecting CH_4 production: the amount and composition of waste placed in every landfill for each year of its operation. The approach used here assumes that the CH_4 generation potential and the rate of decay that produces CH_4, as determined from several studies of CH_4 recovery at landfills, are representative of U.S. landfills.

Additionally, the approach used to estimate the contribution of industrial wastes to total CH_4 generation introduces uncertainty. Aside from uncertainty in estimating CH_4 generation potential, uncertainty exists in the estimates of oxidation by cover soils. There is also uncertainty in the estimates of methane that is recovered by flaring and energy projects. The IPCC default value of 10 percent for uncertainty in recovery estimates was used in the uncertainty analysis when metering was in place (for about 64 percent of the CH_4 estimated to be recovered). For flaring without metered recovery data (approximately 34 percent of the CH_4 estimated to be recovered), a much higher uncertainty of approximately 50 percent was used (e.g., when recovery was estimated as 50 percent of the flare's design capacity).

N_2O emissions from the application of sewage sludge on landfills are not explicitly modeled as part of greenhouse gas emissions from landfills. N_2O emissions from sewage sludge applied to landfills would be relatively small because the microbial environment in landfills is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* (IPCC 2006) did not include a methodology for estimating N_2O emissions from solid waste disposal sites "because they are not significant." Therefore, any uncertainty or bias caused by not including N_2O emissions from landfills is expected to be minimal.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 8-5. Landfill CH_4 emissions in 2007 were estimated to be between 80.6 and 176.2 Tg CO_2 Eq., which indicates a range of 39 percent below to 33 percent above the 2007 emission estimate of 132.9 Tg CO_2 Eq.

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 CH_4 recovery estimates were not double-counted. Both manual and electronic checks were made to ensure that emission avoidance from each landfill was calculated only in one of the three databases. 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

In developing the current Inventory, the data that formed the basis of the industrial food processing waste DOC values were re-analyzed. Based on the re-analysis of the available data for industrial food processing waste, the DOC value for industrial food waste was revised from 0.29 to 0.26 (Coburn 2008). This decrease in food industries' DOC value led to a slight decrease in CH_4 generation and CH_4 emissions from food industry landfills.

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of the amount of waste placed in MSW landfills. Improvements to the flare database will be investigated, and an effort will be made to identify additional landfills that have flares.

Table 8-5: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Landfills	CH_4	132.9	80.6	176.2	-39%	+33%

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

Box 8-1: Biogenic Emissions and Sinks of Carbon

CO_2 emissions from the combustion or decomposition of biogenic materials (e.g., paper, wood products, and yard trimmings) grown on a sustainable basis are considered to mimic the closed loop of the natural carbon cycle—that is, they return to the atmosphere CO_2 that was originally removed by photosynthesis. In contrast, CH_4 emissions from landfilled waste occur due to the man-made anaerobic conditions conducive to CH_4 formation that exist in landfills, and are consequently included in this Inventory.

Depositing wastes of biogenic origin in landfills causes the removal of carbon from its natural cycle between the atmosphere and biogenic materials. As empirical evidence shows, some of these wastes degrade very slowly in landfills, and the carbon they contain is effectively sequestered in landfills over a period of time (Barlaz 1998, 2005). Estimates of carbon removals from landfilling of forest products, yard trimmings, and food scraps are further described in the Land Use, Land-Use Change, and Forestry chapter, based on methods presented in IPCC (2003) and IPCC (2006).

8.2. Wastewater Treatment (IPCC Source Category 6B)

Wastewater treatment processes can produce anthropogenic CH_4, N_2O, and in some cases, CO_2, emissions.[4] Wastewater from domestic (municipal sewage) and industrial sources is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Treatment may either occur on site, most commonly through septic systems or package plants,[5] 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 21 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 2007b).

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 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 biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes, but is more often associated with denitrification.

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.

In 2007, CH_4 emissions from domestic wastewater treatment were 15.8 Tg CO_2 Eq. (755 Gg). Emissions gradually increased from 1990 through 1996, 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. In 2007, CH_4 emissions from industrial wastewater treatment were estimated to be 8.5 Tg CO_2 Eq. (405 Gg). Industrial emission sources have increased across

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[4] Wastewater treatment at petroleum refineries can produce anthropogenic CO_2. Estimates of these emissions are found in the Petroleum Systems section of the Energy chapter.

[5] Package plants are treatment plants assembled in a factory, skid mounted, and transported to the treatment site.

Table 8-6: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
CH_4	**23.5**	**24.8**	**25.2**	**24.3**	**24.5**	**24.4**
Domestic	16.4	16.9	16.8	16.2	16.0	15.8
Industrial[a]	7.1	8.0	8.4	8.2	8.5	8.5
N_2O	**3.7**	**4.0**	**4.5**	**4.8**	**4.8**	**4.9**
Domestic	3.7	4.0	4.5	4.8	4.8	4.9
Total	**27.2**	**28.9**	**29.6**	**29.1**	**29.3**	**29.2**

[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 8-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (Gg)

Activity	1990	1995	2000	2005	2006	2007
CH_4	**1,120**	**1,183**	**1,200**	**1,159**	**1,165**	**1,160**
Domestic	782	804	802	770	762	755
Industrial[a]	338	380	398	389	403	405
N_2O	**12**	**13**	**14**	**15**	**15**	**16**
Domestic	12	13	14	15	15	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.

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.[6] Table 8-6 and Table 8-7 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 2007 emissions of N_2O from centralized wastewater treatment processes and from effluent were estimated to be 0.3 Tg CO_2 Eq. (1 Gg) and 4.6 Tg CO_2 Eq. (15 Gg), respectively. Total N_2O emissions from domestic wastewater were estimated to be 4.9 Tg CO_2 Eq. (16 Gg). N_2O emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

Methodology

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems, such as publicly owned treatment works (POTWs). Within these centralized systems, CH_4 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. CH_4 emissions from septic systems were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated in septic systems (20 percent), the maximum CH_4 producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD), and the MCF for septic systems (0.5). CH_4 emissions from POTWs were estimated by multiplying the total BOD_5 produced in the United States by the percent of wastewater treated centrally (79 percent), the relative percentage of wastewater treated by aerobic and anaerobic systems, the relative percentage of wastewater facilities with primary treatment, the percentage of BOD_5 treated after primary treatment (67.5 percent), the maximum CH_4-producing

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[6] Other industrial sectors include organic chemicals, starch production, alcohol refining, creameries, seafood processing, steam electric power generation, fertilizer manufacturing, and textiles; however, emissions from these sectors are considered to be insignificant.

capacity of domestic wastewater (0.6), and the relative MCFs for aerobic (zero or 0.3) and anaerobic (0.8) systems. CH_4 emissions from anaerobic digesters were estimated by multiplying the amount of biogas generated by wastewater sludge treated in anaerobic digesters by the proportion of CH_4 in digester biogas (0.65), the density of CH_4 (662 g CH_4/m^3 CH_4),[7] and the destruction efficiency associated with burning the biogas in an energy/thermal device (0.99).[8] The methodological equations are:

$$\textit{Emissions from Septic Systems} = A$$
$$= (\%\text{ onsite}) \times (\text{total BOD}_5\text{ produced}) \times (B_o) \times (\text{MCF-septic}) \times 1/10^6$$

$$\textit{Emissions from Centrally Treated Aerobic Systems} = B$$
$$= [(\%\text{ collected}) \times (\text{total BOD}_5\text{ produced}) \times (\%\text{ aerobic}) \times (\%\text{ aerobic w/out primary}) + (\%\text{ collected}) \times (\text{total BOD}_5\text{ produced}) \times (\%\text{ aerobic}) \times (\%\text{ aerobic w/primary}) \times (1\text{-}\%\text{ BOD removed in prim. treat.})] \times (\%\text{ operations not well managed}) \times (B_o) \times (\text{MCF-aerobic\_not\_well\_man.}) \times 1/10^6$$

$$\textit{Emissions from Centrally Treated Anaerobic Systems} = C$$
$$= [(\%\text{ collected}) \times (\text{total BOD}_5\text{ produced}) \times (\%\text{ anaerobic}) \times (\%\text{ anaerobic w/out primary}) + (\%\text{ collected}) \times (\text{total BOD}_5\text{ produced}) \times (\%\text{ anaerobic}) \times (\%\text{ anaerobic w/primary}) \times (1\text{-}\%\text{BOD removed in prim. treat.})] \times (B_o) \times (\text{MCF-anaerobic}) \times 1/10^6$$

$$\textit{Emissions from Anaerobic Digesters} = D$$
$$= [(\text{POTW\_flow\_AD}) \times (\text{digester gas})/(\text{per capita flow})] \times \text{conversion to m}^3 \times (\text{FRAC\_CH}_4) \times (365.25) \times (\text{density of CH}_4) \times (1\text{-DE}) \times 1/10^9$$

$$\text{Total CH}_4\text{ Emissions (Gg)} = A + B + C + D$$

where,

% 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
Total BOD$_5$ produced = kg BOD/capita/day × U.S. population × 365.25 days/yr
B_o = Maximum CH_4-producing capacity for domestic wastewater (0.60 kg CH_4/kg BOD)
MCF-septic = CH_4 correction factor for septic systems (0.5)
$1/10^6$ = Conversion factor, kg to Gg
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 (gal)
digester gas = Cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) (Metcalf and Eddy 1991)

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[7] Based on air at 70° F and 1 atm.

[8] Anaerobic digesters at wastewater treatment plants generated 798 Gg CH_4 in 2006, 790 Gg of which was combusted in flares or energy devices (assuming a 99% destruction efficiency).

per capita flow = Wastewater flow to POTW per person per day (100 gal/person/day)

conversion to m^3 = Conversion factor, ft^3 to m^3 (0.0283)

FRAC_CH_4 = Proportion CH_4 in biogas (0.65)

density of CH_4 = 662 (g CH_4/m^3 CH_4)

$1/10^9$ = Conversion factor, g to Gg

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census 2008a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 8-8 presents U.S. population and total BOD_5 produced for 1990 through 2007. 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, and 2005 American Housing Surveys conducted by the U.S. Census Bureau (U.S. Census 2008b), with data for intervening years obtained by linear interpolation. The wastewater flow to aerobic and anaerobic systems, 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 2004a).[9] Data for intervening years were obtained by linear interpolation. The BOD_5 production rate (0.09 kg/capita/day) for domestic wastewater was obtained from Metcalf and Eddy (1991 and 2003). The CH_4 emission factor (0.6 kg CH_4/kg BOD_5) and the MCFs were taken from IPCC (2006). The CH_4 destruction efficiency, 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 NSPS for landfills, and in recommendations for closed flares used by the LMOP. The cubic feet of digester gas produced per person per day (1.0 ft^3/person/day) and the proportion of CH_4 in biogas (0.65) come from Metcalf and Eddy (1991). 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 (2004), "Recommended Standards for Wastewater Facilities (Ten-State Standards)."

Table 8-8: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (Gg)

Year	Population	BOD_5
1990	254	8,350
1995	271	8,895
2000	287	9,419
2001	289	9,509
2002	292	9,597
2003	295	9,685
2004	297	9,774
2005	300	9,864
2006	303	9,954
2007	306	10,043

Source: U.S. Census Bureau (2008a); Metcalf & Eddy 1991 and 2003.

Industrial Wastewater CH_4 Emission Estimates

CH_4 emissions estimates from industrial wastewater were developed according to the methodology described in IPCC (2006). Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified. High volumes of wastewater generated and a high organic wastewater load were the main criteria. 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 2007 are displayed in Table 8-9.

Table 8-10 contains production data for these industries.

Table 8-9: Industrial Wastewater CH_4 Emissions by Sector for 2007

	CH_4 Emissions (Tg CO_2 Eq.)	% of Industrial Wastewater CH_4
Pulp & Paper	4.1	48%
Meat & Poultry	3.6	43%
Petroleum Refineries	0.6	7%
Fruit & Vegetables	0.1	1%
Ethanol Refineries	0.1	1%
Total	**8.5**	**100%**

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[9] Aerobic and anaerobic treatment were determined based on unit processes in use at the facilities. Because the list of unit processes became more extensive in the 2000 and 2004 surveys, the criteria used to identify aerobic and anaerobic treatment differ slightly across the time series. Once facilities were identified as aerobic or anaerobic, they were separated by whether or not they had anaerobic digestion in place. Once these classifications were determined, the flows associated with facilities in each category were summed.

Table 8-10: U.S. Pulp and Paper; Meat and Poultry; Vegetables, Fruits and Juices Production; and Fuels Production (Tg)

Year	Pulp and Paper	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol	Petroleum Refining
1990	128.9	27.3	14.6	38.7	2.7	702.4
1995	140.9	30.8	18.9	46.9	4.2	735.6
2000	142.8	32.1	22.2	50.9	4.9	795.2
2001	134.3	31.6	22.8	45.0	5.3	794.9
2002	132.7	32.7	23.5	47.7	6.4	794.4
2003	131.9	32.3	23.7	44.7	8.4	804.2
2004	136.4	31.2	24.4	47.8	10.2	821.5
2005	131.4	31.4	25.1	42.7	11.7	818.6
2006	137.4	32.5	25.5	43.5	14.5	826.7
2007	135.9	33.4	26.0	43.5	19.4	827.6

CH_4 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 percentage of organic loading assumed to degrade anaerobically, and the emission factor. 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 CH_4/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 and secondary treatment. 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 methodological equations are:

$$\text{CH}_4 \text{ (industrial wastewater)} = P \times W \times COD \times TA \times B_o \times MCF$$

$$TA = (\%Plants_o \times \%WW_{a,p} \times \%COD_p) + (\%Plants_a \times \%WW_{a,s} \times \%COD_s) + (\%Plants_t \times \%WW_{a,t} \times \%COD_s)$$

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 = Percent of wastewater treated anaerobically on site

$\%Plants_o$ = 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

Table 8-11: Variables Used to Calculate Percent Wastewater Treated Anaerobically by Industry

	Industry						
Variable	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
$\%TA_s$	10.5	33	25	5.5	33.3	75	100
$\%Plants_o$	60	100	100	11	100	100	100
$\%Plants_a$	25	33	25	5.5	33.3	75	100
$\%Plants_t$	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	100	100	100	100

As described below, the values presented in Table 8-11 were used in the inventory calculations.

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. No anaerobic activity is assumed to occur in activated sludge systems or aerated stabilization basins (note: although IPCC recognizes that some CH_4 can be emitted from anaerobic pockets, they recommend an MCF of zero). However, about 25 percent of the wastewater treatment systems used in the United States are non-aerated stabilization basins. These basins are typically 10 to 25 feet deep. These systems are classified as anaerobic deep lagoons (MCF = 0.8).

A time series of CH_4 emissions for 1990 through 2001 was developed based on production figures reported in the Lockwood-Post Directory (Lockwood-Post 2002). Published data from the American Forest and Paper Association, data published by Paper Loop, and other published statistics were used to estimate production for 2002 through 2007 (Pulp and Paper 2005, 2006 and monthly reports from 2003 through 2006; Paper 360° 2007). The overall wastewater outflow was estimated to be 85 m^3/metric ton, and the average BOD concentrations in raw wastewater was estimated to be 0.4 gram BOD/liter (EPA 1997b, EPA 1993, World Bank 1999).

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 B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic lagoons were used to estimate the CH_4 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 2008a). Data collected by EPA's Office of Water provided estimates for wastewater flows into anaerobic lagoons: 5.3 and 12.5 m^3/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.

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 B_o of 0.25 kg CH_4/kg COD and default MCF of 0.8 for anaerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems. The USDA National Agricultural Statistics Service (USDA 2008a) provided production data for potatoes, other vegetables, citrus fruit, non-citrus fruit, and grapes processed for wine. Outflow and BOD data, presented in Table 8-12, were obtained from EPA (1974) for potato, citrus fruit, and apple processing, and from EPA (1975) for all other sectors.

Table 8-12: Wastewater Flow (m^3/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	8.81	0.808
Fruit		
Apples	3.66	1.371
Citrus	10.11	0.317
Non-citrus	12.42	1.204
Grapes (for wine)	2.78	1.831

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 Department of Energy predicts cellulosic ethanol to greatly increase in the coming years, currently it is only in an experimental stage in the United States. According to the Renewable Fuels Association, 82 percent of ethanol production facilities use corn as the sole feedstock and 7 percent of facilities use a combination of corn and another starch-based feedstock. The fermentation of corn is the principal ethanol production process in the United States and is expected to increase for at least the next 6 years, and potentially more; therefore, emissions associated with wastewater treatment at starch-based ethanol production facilities were estimated (ERG 2006).

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 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. CH_4 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,b; Merrick 1998; Donovan 1996; and NRBP 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 methane is recovered through the use of biomethanators (ERG 2006). CH_4 emissions were then estimated as follows:

$$\begin{aligned}
\text{Methane} = \{&\text{Production} \times \text{Flow} \times \text{COD} \times 3.785 \times \\
&[(\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p) + \\
&(\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s) + \\
&(\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s)] \times \\
&B_o \times \text{MCF} \times \%\ \text{Not Recovered}\} + \\
\{&\text{Production} \times \text{Flow} \times 3.785 \times \text{COD} \times \\
&[(\%\text{Plants}_o \times \%\text{WW}_{a,p} \times \%\text{COD}_p) + \\
&(\%\text{Plants}_a \times \%\text{WW}_{a,s} \times \%\text{COD}_s) + \\
&(\%\text{Plants}_t \times \%\text{WW}_{a,t} \times \%\text{COD}_s)] \times \\
&B_o \times \text{MCF} \times \%\ \text{Recovered} \times (1\text{-DE})\} \times 1/10^9
\end{aligned}$$

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

$\%\text{Plants}_o$ = percent of plants with onsite treatment (100%)

$\%\text{WW}_{a,p}$ = percent of wastewater treated anaerobically in primary treatment (0%)

$\%\text{COD}_p$ = percent of COD entering primary treatment (100%)

$\%\text{Plants}_a$ = percent of plants with anaerobic secondary treatment (33.3% wet, 75% dry)

$\%\text{Plants}_t$ = percent of plants with other secondary treatment (66.7% wet, 25% dry)

$\%\text{WW}_{a,s}$ = percent of wastewater treated anaerobically in anaerobic secondary treatment (100%)

$\%\text{WW}_{a,t}$ = percent of wastewater treated anaerobically in other secondary treatment (0%)

$\%\text{COD}_s$ = 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 Gg

A time series of CH_4 emissions for 1990 through 2007 was developed based on production data from the Renewable Fuels Association (RFA 2005).

Petroleum Refining. Petroleum refining wastewater treatment operations produce CH_4 emissions from anaerobic wastewater treatment. The wastewater inventory section includes CH_4 emissions from petroleum refining wastewater treated on site under intended or unintended anaerobic conditions. Most facilities use aerated biological systems, such as trickling filters or rotating biological contactors; these systems can also exhibit anaerobic conditions that can result in the production of methane. Oil/water separators are used as a primary treatment method; however, it is unlikely that any COD is removed in this step.

Available information from the industry was compiled. The wastewater generation rate, from CARB 2007 and Timm 1985, was determined to be 35 gallons per barrel of finished product. An average COD value in the wastewater was estimated at 0.45 kg/m^3 (Benyahia et al.).

The equation used to calculate CH_4 generation at petroleum refining wastewater treatment systems is presented below:

$$\text{Methane} = \text{Flow} \times \text{COD} \times B_o \times \text{MCF}$$

Where:

Flow = Annual flow treated through anaerobic treatment system (m^3/year)

COD = COD loading in wastewater entering anaerobic treatment system (kg/m^3)

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 CH_4 emissions for 1990 through 2007 was developed based on production data from the Energy Information Association (EIA 2008).

Domestic Wastewater N_2O Emission Estimates

N_2O 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 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.[10]
- 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.[11]
- Small amounts of gaseous nitrogen oxides are formed as byproducts in the conversion of nitrate to N_2 gas in anoxic biological treatment systems. Approximately 7 grams NO is generated per capita per year if wastewater treatment includes intentional nitrification and denitrification (Scheehle and Doorn 2001) Analysis of the 2000 CWNS shows there are 88 treatment plants in the United States, serving a population of 2.6 million people, with denitrification as one of their unit operations. Based on an emission factor of 7 grams/capita/year, approximately 17.5 metric tons of additional N_2O may have been emitted via denitrification in 2000. 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 grams N_2O per capita per year.

With the modifications described above, N_2O emissions from domestic wastewater were estimated using the following methodology:

$$N_2O_{TOTAL} = N_2O_{PLANT} + N_2O_{EFFLUENT}$$

$$N_2O_{PLANT} = N_2O_{NIT/DENIT} + N_2O_{WOUT\ NIT/DENIT}$$

$$N_2O_{NIT/DENIT} = [US_{POPND} \times EF_2 \times F_{IND\text{-}COM}] \times 1/10^9$$

$$N_2O_{WOUT\ NIT/DENIT} = \{[(US_{POP} \times WWTP) - US_{POPND} \times F_{IND\text{-}COM}] \times EF_1\} \times 1/10^9$$

$$N_2O_{EFFLUENT} = \{[((US_{POP} - (0.9 \times US_{POPND})) \times Protein \times F_{NPR} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}) - N_{SLUDGE}] \times EF_3 \times 44/28\} \times 1/10^6$$

where,

N_2O_{TOTAL} = Annual emissions of N_2O (kg)

N_2O_{PLANT} = N_2O emissions from centralized wastewater treatment plants (kg)

$N_2O_{NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (kg)

$N_2O_{WOUT\ NIT/DENIT}$ = N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (kg)

$N_2O_{EFFLUENT}$ = N_2O emissions from wastewater effluent discharged to aquatic environments (kg)

US_{POP} = U.S. population

US_{POPND} = U.S. population that is served by biological denitrification (from CWNS)

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[10] The methodology for estimating the quantity of sewage sludge N not entering aquatic environments is described in Annex 3.11.

[11] ERG identified two data sources needed to determine the consumption factor. The first source is Table 7 of USDA's Nutrient Content of the U.S. Food Supply, 1909–2004 Summary Report, which presents a time series percentage of protein contributed by major food groups to the U.S. food supply. The second source is Table 1 from Kantor (1997), which presents the percentage of loss from the edible food supply by major food groups. Using data from these two sources, one can calculate a time series of factors of protein loss.

WWTP = Fraction of population using WWTP (as opposed to septic systems)

EF_1 = Emission factor (3.2 g N_2O/person-year)

EF_2 = Emission factor (7 g N_2O/person-year)

Protein = Annual per capita protein consumption (kg/person/year)

F_{NPR} = Fraction of N in protein, default = 0.16 (kg N/kg protein)

$F_{NON\text{-}CON}$ = Factor for non-consumed protein added to wastewater (1.4)

$F_{IND\text{-}COM}$ = 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)

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 2008a) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. The fraction of the U.S. population using wastewater treatment plants is based on data from the 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, and 2005 American Housing Survey (U.S. Census 2008b). Data for intervening years were obtained by linear interpolation. The emission factor (EF_1) used to estimate emissions from wastewater treatment was taken from IPCC (2006). Data on annual per capita protein intake were provided by U.S. Department of Agriculture Economic Research Service (USDA 2008b). Protein consumption data for 2005 through 2007 were extrapolated from data for 1990 through 2004. Table 8-13 presents the data for U.S. population and average protein intake. 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. The fraction of N in protein (0.16 kg N/kg protein) was also 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 2007 were forecasted from the rest of the time series. An estimate for the nitrogen 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. In 2007, 266 Tg N was removed with sludge.

Table 8-13: U.S. Population (Millions), Available Protein [kg/(person-year)], and Protein Consumed [kg/(person-year)]

Year	Population	Available Protein	Protein Consumed
1990	254	38.7	29.6
1995	271	39.8	30.4
2000	287	41.3	31.6
2001	289	42.0	32.1
2002	292	40.9	31.3
2003	295	40.9	31.3
2004	297	41.3	31.6
2005	300	41.7	32.1
2006	303	41.9	32.1
2007	306	42.1	32.2

Source: U.S. Census Bureau (2008a), USDA (2008b).

Uncertainty

The overall uncertainty associated with both the 2007 CH_4 and N_2O emissions estimates from wastewater treatment and discharge was calculated using the IPCC Good Practice Guidance Tier 2 methodology (2000). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater, and wastewater from pulp and paper manufacture, meat and poultry processing, fruit and vegetable processing, ethanol production, and petroleum refining. Uncertainty associated with the parameters used to estimate N_2O 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.

Table 8-14: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Wastewater Treatment ($Tg\ CO_2$ Eq. and Percent)

Source	Gas	2007 Emission Estimate ($Tg\ CO_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] ($Tg\ CO_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**24.4**	**15.1**	**36.3**	**-38%**	**+49%**
Domestic	CH_4	15.8	7.7	27.0	-51%	+70%
Industrial	CH_4	8.5	5.1	13.1	-40%	+54%
Domestic Wastewater Treatment	**N_2O**	**4.9**	**1.2**	**9.4**	**-75%**	**+94%**

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

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 8-14. CH_4 emissions from wastewater treatment were estimated to be between 15.1 and 36.3 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 38 percent below to 49 percent above the 2007 emissions estimate of 24.4 Tg CO_2 Eq. N_2O emissions from wastewater treatment were estimated to be between 1.2 and 9.4 Tg CO_2 Eq., which indicates a range of approximately 75 percent below to 94 percent above the actual 2007 emissions estimate of 4.9 Tg CO_2 Eq.

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

The estimates of CH_4 emissions from industrial wastewater treatment increased across the time series as petroleum refining wastewater treatment was added to the Inventory. The addition of this industrial sector increased industrial wastewater estimates by 9.0 to 9.8 percent across the time series.

For treatment of the fruit and vegetable processing industry, a factor to account for the removal of organics as sludge prior to anaerobic treatment was added. Based on data collected by EPA (1975), BOD is typically reduced by 17 to 30 percent, so a removal rate of 23 percent was used in the Inventory.

Finally, the calculations of the percent of industrial wastewater treated anaerobically (%TA) were revised. A general calculation for each industry defines 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. The %TA was estimated for both primary treatment and secondary treatment.

Overall, the CH_4 emission estimates for wastewater treatment are on average 0.5 percent greater than the previous Inventory.

For N_2O emissions from domestic wastewater, a major refinement to the calculation was the reestimation of per capita protein consumption to account for the amount consumed, not simply all protein available for consumption. In addition, the N_2O emission calculation was updated. The (US_{POP}) component of the $N_2O_{EFFLUENT}$ equation was replaced with [US_{POP} – ($0.9\times US_{POPND}$)] to more accurately represent the nitrogen loading of wastewater discharged to aquatic environments. By making that replacement, the N lost as N_2O from centralized treatment systems was subtracted from the estimate of nitrogen discharged to the environment to account for loss from nitrification/denitrification systems. Overall, the N_2O emissions estimates for wastewater treatment are on average 41 percent lower than the previous Inventory.

Overall, emissions from wastewater treatment and discharge (CH_4 and N_2O) decreased by an average of approximately 9 percent from the previous Inventory.

Planned Improvements Discussion

The methodology to estimate CH_4 emissions from domestic wastewater treatment currently utilizes estimates for the percentage of centrally treated wastewater that is treated by aerobic systems and anaerobic systems. These data come from the 1992, 1996, 2000, and 2004 CWNS. The designation of systems as aerobic or anaerobic has been further refined to differentiate aerobic systems with the potential to generate small amounts of CH_4 (aerobic lagoons) versus other types of aerobic systems, and to differentiate between anaerobic systems to allow for the use of different MCFs for different types of anaerobic treatment systems. Currently, it is assumed that all aerobic systems are well managed and produce no CH_4, all aerobic systems that have some anaerobic activity have an MCF of 0.3, and that all anaerobic systems have an MCF of 0.8. Efforts to obtain better data reflecting emissions from various types of municipal treatment systems are currently being pursued.

For the current Inventory, an attempt was made to refine the designation of unit operations from aerobic and anaerobic to include an aerobic/anaerobic designation for some of the treatment systems that were previously designated anaerobic. However, the available data are not sufficiently detailed across the time series to complete this designation.

Other potential sources of CH_4 and CO_2 emissions from wastewater treatment at petroleum refineries will be investigated. Also, available data on wastewater treatment emissions at organic chemical manufacturers will be reviewed to determine if this is a significant source to be included in future versions of the Inventory.

With respect to estimating N_2O emissions, the default emission factor for N_2O from wastewater effluent has a high uncertainty. The IPCC recently updated this factor; however, future research may identify new studies that include updated data. The factor that accounts for non-sewage nitrogen in wastewater (bath, laundry, kitchen, industrial components) also has a high uncertainty. Obtaining data on the changes in average influent nitrogen concentrations to centralized treatment systems over the time series would improve the estimate of total N entering the system, which would reduce or eliminate the need for other factors for non-consumed protein or industrial flow. In addition there is uncertainty associated with the N_2O emission factors for direct emissions from centralized wastewater treatment facilities. Efforts to gain greater confidence in these emission factors are currently being pursued.

8.3. Composting (IPCC Source Category 6D)

Composting of organic waste, such as food waste, garden (yard) and park waste and sludge, is common in the United States. Advantages of composting include reduced volume in the waste material, stabilization of the waste, and destruction of pathogens in the waste material. The end product of composting, depending on its quality, can be recycled as 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 CO_2. Methane is formed in anaerobic sections of the compost, but it is oxidized to a large extent in the aerobic sections of the compost. Anaerobic sections are created in composting piles when there is excessive moisture or inadequate aeration (or mixing) of the compost pile. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Composting can also produce emissions of N_2O. The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006).

Table 8-15: CH_4 and N_2O Emissions from Composting (Tg CO_2 Eq.)

Activity	1990	1995	2000	2005	2006	2007
CH_4	0.3	0.7	1.3	1.6	1.6	1.7
N_2O	0.4	0.8	1.4	1.7	1.8	1.8
Total	**0.7**	**1.5**	**2.6**	**3.3**	**3.3**	**3.5**

Table 8-16: CH_4 and N_2O Emissions from Composting (Gg)

Activity	1990	1995	2000	2005	2006	2007
CH_4	15	35	60	75	75	79
N_2O	1	3	4	6	6	6

From 1990 to 2007, the amount of material composted in the United States has increased from 3,810 Gg to 19,695 Gg, an increase of approximately 400 percent. Emissions of CH_4 and N_2O from composting have increased by the same percentage (see Table 8-15 and Table 8-16). In 2007, CH_4 emissions from composting were 1.7 Tg CO_2 Eq. (79 Gg), and N_2O emissions from composting were 1.8 Tg CO_2 Eq. (6 Gg). The wastes that are composted include primarily yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from residences and commercial establishments (such as grocery stores, restaurants, and school and factory cafeterias). The composting waste quantities reported here do not include backyard composting. The growth in composting is attributable primarily to two factors: (1) steady growth in population and residential housing, and (2) state and local governments enacting legislation that discouraged the disposal of yard trimmings in landfills. In 1992, 11 states and the District of Columbia had legislation in effect that banned or discouraged disposal of yard trimmings in landfills. In 2005, 21 states and the District of Columbia, representing about 50 percent of the nation's population, had enacted such legislation (EPA 2006).

Methodology

CH_4 and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process.

The emissions shown in Table 8-15 and Table 8-16 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations):

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, Gg CH_4 or N_2O,

M = mass of organic waste composted in Gg,

EF_i = emission factor for composting, 4 g CH_4/kg of waste treated (wet basis) and 0.3 g N_2O/kg of waste treated (wet basis), and

i = designates either CH_4 or N_2O.

Estimates of the quantity of waste composted (M) are presented in Table 8-17. Estimates of the quantity composted for 1990 and 1995 were taken from the *Characterization of Municipal Solid Waste in the United States: 1996 Update* (Franklin Associates 1997); estimates of the quantity composted for 2000, 2005, 2006, and 2007 were taken from EPA's *Municipal Solid Waste In The United States: 2007 Facts and Figures* (EPA 2008).

Table 8-17: U.S. Waste Composted (Gg)

Activity	1990	1995	2000	2005	2006	2007
Waste Composted	3,810	8,682	14,923	18,643	18,852	19,695

Source: Franklin Associates (1997) and EPA (2008).

Table 8-18: Tier 1 Quantitative Uncertainty Estimates for Emissions from Composting (Tg CO_2 Eq. and Percent)

Source	Gas	2007 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4, N_2O	3.5	1.7	5.2	-50%	+50%

Uncertainty

The estimated uncertainty from the *2006 IPCC Guidelines* (IPCC 2006) is ±50 percent for the Tier 1 methodology. Emissions from composting in 2007 were estimated to be between 1.7 and 5.2 Tg CO_2 Eq., which indicates a range of 50 percent below to 50 percent above the actual 2007 emission estimate of 3.5 Tg CO_2 Eq. (see Table 8-18).

Planned Improvements

For future Inventories, additional efforts will be made to improve the estimates of CH_4 and N_2O emissions from composting. For example, a literature search may be conducted to determine if emission factors specific to various composting systems and composted materials are available.

8.4. 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 NO_x, CO, and NMVOCs from waste sources for the years 1990 through 2007 are provided in Table 8-19.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emission estimates of these gases were provided by

Table 8-19: Emissions of NO_x, CO, and NMVOCs from Waste (Gg)

Gas/Source	1990	1995	2000	2005	2006	2007
NO_x	**+**	**1**	**2**	**2**	**2**	**2**
Landfills	+	1	2	2	2	2
Wastewater Treatment	+	+	+	+	+	+
Miscellaneous[a]	+	1	+	+	+	+
CO	**1**	**2**	**8**	**7**	**7**	**7**
Landfills	1	2	7	6	6	6
Wastewater Treatment	+	+	1	+	+	+
Miscellaneous[a]	+	1	+	+	+	+
NMVOCs	**673**	**731**	**119**	**115**	**113**	**111**
Wastewater Treatment	58	68	22	22	21	21
Miscellaneous[a]	57	61	51	50	49	48
Landfills	557	602	46	44	43	42

+ Does not exceed 0.5 Gg.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

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 source categories from various agencies. Depending on the source category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which 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

No quantitative estimates of uncertainty were calculated for this source category. Uncertainties in these estimates, however, are primarily due to the accuracy of the emission factors used and accurate estimates of activity data.

9. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) "Other" sector.

10. 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 Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance* (IPCC 2000), which states, "It is good practice to recalculate historic emissions when methods are changed or refined, when new source categories are included in the national inventory, or when errors in the estimates are identified and corrected."

The results of all methodology changes and historical data updates are presented in this section; detailed descriptions of each recalculation are contained within each source's description contained in this report, if applicable. Table 10-1 summarizes the quantitative effect of these changes on U.S. greenhouse gas emissions and Table 10-2 provides greater detail regarding the quantitative effect of these changes in the Land Use, Land-Use Change, and Foresty sector, both relative to the previously published U.S. Inventory (i.e., the 1990 through 2006 report). These tables present the magnitude of these changes in units of teragrams of carbon dioxide equivalent (Tg CO_2 Eq.).

The Recalculations Discussion section of each source presents the details of each recalculation. In general, when methodological changes have been implemented, the entire time series (i.e., 1990 through 2006) has been recalculated to reflect the change, per IPCC (2000). Changes in historical data are generally the result of changes in statistical data supplied by other agencies.

The following emission sources, which are listed in descending order of absolute average annual change in emissions between 1990 and 2006, underwent some of the most important methodological and historical data changes. A brief summary of the recalculation and/or improvement undertaken is provided for each emission source.

- *Net CO_2 Flux from Land Use, Land-Use Change, and Forestry.* Changes in the Land Use, Land-Use Change, and Forestry sector occurred primarily in calculations for forest and grassland carbon (C) stock and flux estimates. The most significant changes were in forest aboveground biomass and soil organic carbon within the *Forest Land Remaining Forest Land* land-use category and in the *Grassland Remaining Grassland* land-use category. In the estimation of forest C stocks within the *Forest Land Remaining Forest Land* land-use category, newly available state data contributed to the recalculations in the flux of carbon dioxide to the atmosphere. Changes in calculation methodology for state-level estimates, particularly in the scaling up of plot-level stock estimates and in extrapolating C stock and stock change, resulted in significant change in the net forest C flux. With regard to C stock recalculation for *Grassland Remaining Grassland*, several changes to historical estimates resulted from the incorporation of annual survey data from the USDA National Resources Inventory (NRI) in the 1990–2007 Inventory. These changes included: (1) the availability of new data extended the time series of activity data beyond 1997 to 2003; (2) annual area data were used to estimate soil C stock changes, rather than data collected in 5-year increments; (3) each NRI point was simulated separately, instead of simultaneously; and, (4) NRI area data were reconciled with Forest Inventory and Analysis (FIA) area data, which led to adjustments in the NRI dataset. Overall, these changes, in combination with smaller adjustments in the other sources/sinks within the sector, resulted in an average annual decrease in *net* flux of CO_2 to the atmosphere from the Land Use, Land-Use Change, and Forestry sector of 117.3 Tg CO_2 Eq. (14.1 percent) for the period 1990 through 2006, as compared to estimates presented in the previous Inventory.

- *Agricultural Soil Management.* Changes in the estimates of N_2O emissions from Agricultural Soil Management occurred primarily due to a new operational version of the DAYCENT model and revised structural uncertainty associated with the model. Improvements to the DAYCENT model include elimination of the influence of labile (i.e., easily decomposable by microbes) C availability on surface litter denitrification rates, incorporation of precipitation events as a controlling variable on surface litter denitrification, and allowing the wettest soil layer within the rooting zone to control plant transpiration. Overall, changes resulted in an average annual decrease in nitrous oxide (N_2O) emissions from Agricultural Soil Management of 61.3 Tg CO_2 Eq. (22.7 percent) for the period 1990 through 2006.
- *Iron and Steel Production.* Estimates of CO_2 from iron and steel production have been revised to adhere to the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Previously the estimates focused primarily on the consumption of coking coal to produce metallurgical coke and the consumption of metallurgical coke, carbon anodes, and scrap steel to produce iron and steel. The revised estimates differentiate between emissions associated with metallurgical coke production and those associated with iron and steel production and include CO_2 emissions from the consumption of other materials such as natural gas, fuel oil, flux (e.g. limestone and dolomite use), direction injection goal, sinter, pellets, and natural ore during the iron and steel production process as well as the metallurgical coke production process. Overall, changes to the Iron and Steel Production estimate resulted in an average annual increase in CO_2 emissions of 26.1 Tg CO_2 Eq. (40.7 percent) for the period 1990 through 2006.
- *Fossil Fuel Combustion.* Estimates of CO_2 from the industrial sector have been revised for the years 1990 through 2006 to subtract for non-energy related consumption of coal, distillate fuel, and natural gas used to produce pig iron in iron and steel and metallurgical coke production. A discussion of the methodology used to estimate non-energy related consumption is contained in the Iron and Steel Production and Metallurgical Coke Production section of the Industrial Processes chapter. Additionally, the Energy Information Administration (EIA 2008b) updated energy consumption data for all years. These revisions primarily impacted the emission estimates for 2006. Overall, changes resulted in an average annual decrease in CO_2 emissions from Fossil Fuel Combustion of 17 Tg CO_2 Eq. (0.3 percent) for the period 1990 through 2006.
- *Enteric Fermentation.* Changes in the estimates of methane (CH_4) emissions from Enteric Fermentation occurred as a result of (1) including additional heifer and steer stocker populations; (2) adjusting the Cattle Enteric Fermentation Model (CEFM) to allow feedlot placements for the 700–800 lbs category to use excess animals from the over 800 lbs category if insufficient animals are available to place in a given month at 700–800 lbs; (3) adjusting animal weights used in calculations; (4) using revised USDA population estimates that affected historical emissions estimated for swine in 2006; and (5) some historical population estimates for certain beef and dairy populations were also updated as a result of changes in USDA inputs. Overall, changes resulted in an average annual increase in CH_4 emissions from Enteric Fermentation of 10.2 Tg CO_2 Eq. (8.1 percent) from 1990 through 2006.
- *Natural Gas Systems.* Changes in the estimates of CH_4 emissions from this source category resulted primarily from the substitution of activity factors with direct data for all years to adapt the natural gas inventory to publicly available data and adjust the current inventory to better reflect emissions from these sources. Overall, changes resulted in an average annual increase in CH_4 emissions from Natural Gas Systems of 4.3 Tg CO_2 Eq. (3.5 percent) for the period 1990 through 2006.
- *Non-Energy Use of Fuels.* Changes in CO_2 emissions estimates from Non-Energy Use of Fuels resulted from

changes in assumptions pertaining to petroleum coke. Non-energy end uses for petroleum coke (other than in the industrial processing sectors, where it is accounted for separately) had not been identified in the past. This year, it was assumed that petroleum coke used for non-energy purposes (and not accounted for in the industrial processes chapter, viz., for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, ammonia, urea, and ferroalloys) is used in pigments, with a storage factor of 0.3 (rather than the value of 0.5 used previously). Overall, the changes resulted in an average annual increase in CO_2 emissions from Non-Energy Use of Fuels of 3.9 Tg CO_2 Eq. (2.9 percent) for the period 1990 through 2006.

- *Nitric Acid Production*. Changes in the estimates of N_2O emissions from Nitric Acid Production were mostly due to adjusting the weighted N_2O emission factor (kg N_2O/metric ton HNO_3), which resulted in an increase in emissions across the time series. The weighted N_2O emission factor was previously based on the percentage of facilities equipped and not equipped with non-selective catalytic reduction (NSCR) systems. The emission factor used for the current estimate is based on the percentage of HNO_3 produced at plants with NSCR systems and HNO_3 produced at plants without NSCR systems. Overall, changes resulted in an average annual increase in N_2O emissions from Nitric Acid Production of 3.1 Tg CO_2 Eq. (17.8 percent) for the period 1990 through 2006.
- *Wastewater Treatment*. Changes in N_2O emissions estimates from domestic wastewater resulted primarily from a major refinement to the calculation—per capita protein consumption was reestimated to account for the amount consumed, not simply all protein available for consumption. In addition, the N_2O emission calculation was updated to more accurately represent the N loading of wastewater discharged to aquatic environments. Overall, changes resulted in an average annual decrease in N_2O emissions from Wastewater Treatment of 3.0 Tg CO_2 Eq. (41.0 percent) for the period 1990 through 2006.
- *Forest Land Remaining Forest Land*. Changes in CH_4 emissions from *Forest Land Remaining Forest Land* resulted primarily from updated carbon density values, combustion factors, and the inclusion of prescribed fires. The carbon density for Alaska was revised to reflect the entire area that the U.S. Forest Service uses to report carbon, and the default IPCC combustion factor for forests was used to replace the previous combustion factor. Emissions from prescribed fires in the United States were included in this year's estimates. Finally, data for land area under wildland fire protection were updated. Overall, changes resulted in an average annual increase in CH_4 emissions from *Forest Land Remaining Forest Land* of 1.8 Tg CO_2 Eq. (20.0 percent) for the period 1990 through 2006.

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2004	2005	2006
CO_2	**8.2**	**13.7**	**15.5**	**9.9**	**16.5**	**31.8**
Fossil Fuel Combustion	(15.2)	(18.5)	(15.6)	(12.0)	(7.6)	(2.5)
Electricity Generation	0.1	(0.4)	0.9	0.4	0.8	(0.8)
Transportation	(0.6)	(0.7)	2.1	4.0	11.6	24.8
Industrial	(10.7)	(13.9)	(15.8)	(13.1)	(19.3)	(17.7)
Residential	(2.4)	(2.1)	(1.7)	(2.0)	(0.5)	(4.7)
Commercial	(1.6)	(1.4)	(1.1)	(1.3)	(0.2)	(4.1)
US Territories	NC	NC	NC	NC	+	(0.1)
Non-Energy Use of Fuels	(0.2)	4.2	3.0	0.4	(1.0)	7.2
Iron and Steel Production & Metallurgical Coke Production	23.5	28.4	28.5	23.3	26.6	27.0
Cement Production	NC	NC	NC	NC	NC	0.8
Natural Gas Systems	+	+	+	+	+	1.0
Incineration of Waste	NC	NC	+	(1.5)	(1.1)	(1.1)
Lime Production	(0.5)	(0.7)	(0.8)	(0.7)	(0.8)	(0.7)

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Gas/Source	1990	1995	2000	2004	2005	2006
Ammonia Production and Urea Consumption	(0.1)	+	+	+	+	(0.1)
Cropland Remaining Cropland	NC	NC	NC	NC	NC	(0.1)
Limestone and Dolomite Use	(0.4)	(0.7)	(0.9)	(0.8)	(0.6)	(0.6)
Aluminum Production	NC	NC	NC	NC	(0.1)	(0.1)
Soda Ash Production and Consumption	NC	NC	NC	NC	NC	NC
Petrochemical Production	NC	NC	NC	NC	NC	NC
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	0.1
Ferroalloy Production	NC	NC	NC	NC	NC	NC
Phosphoric Acid Production	NC	NC	NC	NC	NC	NC
Wetlands Remaining Wetlands[a]	1.0	1.0	1.2	1.2	1.1	0.9
Zinc Production	NC	NC	NC	NC	NC	NC
Petroleum Systems	+	+	+	+	+	+
Lead Production	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	+	+	+	+	+	+
Land Use, Land-Use Change, and Forestry (Sink)[b]	*(103.8)*	*(75.6)*	*(43.9)*	*(420.9)*	*(244.1)*	*(166.9)*
Wood Biomass and Ethanol Consumption[b]	*NC*	+	+	+	*4.1*	*5.7*
International Bunker Fuels[b]	*0.6*	*1.0*	*(2.2)*	*(4.1)*	*(11.1)*	*(16.6)*
CH_4	**10.5**	**16.9**	**16.8**	**17.2**	**22.0**	**26.7**
Enteric Fermentation	6.3	11.2	9.8	11.4	11.5	12.0
Landfills	(0.4)	0.2	1.5	3.6	4.2	4.8
Natural Gas Systems	4.9	4.5	4.3	4.0	3.8	2.4
Coal Mining	NC	NC	0.1	(1.6)	+	(0.1)
Manure Management	(0.6)	(0.7)	(0.9)	(0.3)	0.1	0.4
Forest Land Remaining Forest Land	0.1	1.5	1.7	(0.3)	1.9	6.7
Petroleum Systems	+	+	+	+	+	(0.1)
Wastewater Treatment	0.5	0.5	0.6	0.6	0.6	0.6
Stationary Combustion	+	+	+	+	0.2	0.1
Rice Cultivation	NC	NC	NC	NC	NC	NC
Abandoned Underground Coal Mines	NC	NC	NC	+	+	0.1
Mobile Combustion	+	+	+	+	+	0.1
Composting	NC	NC	NC	NC	NC	NC
Petrochemical Production	+	+	+	0.1	+	+
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	+
Iron and Steel Production & Metallurgical Coke Production	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)
Ferroalloy Production	NC	NC	NC	NC	NC	NC
Silicon Carbide Production and Consumption	NC	NC	NC	NC	NC	NC
International Bunker Fuels[b]	+	+	+	+	+	+
N_2O	**(68.4)**	**(61.5)**	**(56.7)**	**(35.7)**	**(54.1)**	**(55.8)**
Agricultural Soil Management	(69.0)	(62.5)	(57.6)	(35.7)	(54.6)	(56.5)
Mobile Combustion	0.2	0.2	0.3	0.3	0.4	0.5
Nitric Acid Production	3.0	3.4	3.3	2.7	2.8	2.6
Manure Management	+	0.1	0.3	0.3	0.3	0.3
Stationary Combustion	+	+	(0.1)	(0.1)	+	+
Adipic Acid Production	NC	NC	NC	NC	NC	NC
Wastewater Treatment	(2.6)	(2.8)	(3.1)	(3.2)	(3.2)	(3.3)
N_2O from Product Uses	NC	NC	NC	NC	NC	NC
Forest Land Remaining Forest Land	+	0.1	0.2	(0.1)	0.2	0.6

Table 10-1: Revisions to U.S. Greenhouse Gas Emissions (Tg CO_2 Eq.) (continued)

Gas/Source	1990	1995	2000	2004	2005	2006
Composting	NC	NC	NC	NC	NC	NC
Settlements Remaining Settlements	+	+	+	+	+	0.1
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	+
Incineration of Waste	NC	NC	NC	NC	+	+
Wetlands Remaining Wetlands[a]	+	+	+	+	+	+
International Bunker Fuels[b]	*0.1*	*0.1*	+	+	*(0.1)*	*(0.1)*
HFCs	**NC**	**+**	**+**	**(4.2)**	**(5.3)**	**(5.5)**
Substitution of Ozone Depleting Substances	NC	+	+	(4.2)	(5.3)	(5.5)
HCFC-22 Production	NC	NC	NC	NC	NC	NC
Semiconductor Manufacture	NC	+	+	+	+	+
PFCs	**NC**	**+**	**+**	**+**	**+**	**+**
Aluminum Production	NC	NC	NC	NC	+	NC
Semiconductor Manufacture	NC	+	+	+	+	+
SF_6	**0.1**	**0.1**	**0.1**	**(0.2)**	**(0.3)**	**(0.3)**
Electrical Transmission and Distribution	0.1	0.1	0.1	0.1	0.1	+
Magnesium Production and Processing	NC	NC	NC	(0.3)	(0.4)	(0.3)
Semiconductor Manufacture	NC	+	+	+	+	+
Net Change in Total Emissions[c]	**(49.6)**	**(30.7)**	**(24.4)**	**(13.0)**	**(21.3)**	**(3.1)**
Percent Change	**-0.8%**	**-0.5%**	**-0.3%**	**-0.2%**	**-0.3%**	**0.0%**

+ Absolute value does not exceed 0.05 Tg CO_2 Eq. or 0.05 percent.
NC (No Change)

[a] New source category relative to previous Inventory.

[b] Not included in emissions total.

[c] Excludes net CO_2 flux from Land Use, Land-Use Change, and Forestry, and emissions from International Bunker Fuels and Wood Biomass and Ethanol Consumption.

Note: Totals may not sum due to independent rounding.

Table 10-2: Revisions to Net Flux of CO_2 to the Atmosphere from Land Use, Land-Use Change, and Forestry (Tg CO_2 Eq.)

Component: Net CO_2 Flux From Land Use, Land-Use Change, and Forestry	1990	1995	2000	2004	2005	2006
Forest Land Remaining Forest Land	(39.4)	(26.7)	38.1	(408.7)	(232.1)	(155.2)
Cropland Remaining Cropland	0.7	16.4	8.2	22.7	22.7	22.7
Land Converted to Cropland	(12.6)	(6.4)	(7.0)	(3.4)	(3.4)	(3.4)
Grassland Remaining Grassland	(44.9)	(53.0)	(67.8)	(20.9)	(20.9)	(20.9)
Land Converted to Grassland	(8.0)	(6.2)	(15.6)	(10.4)	(10.4)	(10.4)
Settlements Remaining Settlements	NC	NC	NC	NC	NC	NC
Other	0.4	0.2	0.2	(0.3)	(0.2)	0.2
Net Change in Total Flux	**(103.8)**	**(75.6)**	**(43.9)**	**(420.9)**	**(244.1)**	**(166.9)**
Percent Change	**-14.1%**	**-9.8%**	**-6.5%**	**-48.2%**	**-27.8%**	**-18.9%**

NC (No Change)
Note: Numbers in parentheses indicate a decrease in estimated net flux of CO_2 to the atmosphere or an increase in net sequestration.
Totals may not sum due to independent rounding.

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All data tables of this document are available for the full time series 1990 through 2007, inclusive, at the internet site mentioned above.

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

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Greenhouse Gases

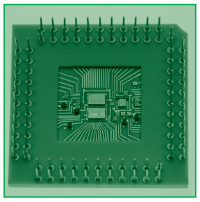
The photos on the front and back cover of this report depict the types of greenhouse gases covered in the 1990–2007 Inventory. This Inventory presents emissions of carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Of these, carbon dioxide is emitted in the largest quantities in the United States, so three of the pictures below depict sources and sinks of carbon dioxide, while sources of each of the other gases are represented in one picture each.

Carbon Dioxide: Land Use, Land-Use Change, and Forestry

Forests and soils in the United States are a net sink for carbon dioxide, offsetting about 17 percent of emissions in 2007. The sink has increased by about 26 percent since 1990. Soils can also be a source of carbon dioxide: liming of agricultural soils and urea application to cropland both lead to a small amount of carbon dioxide emissions.

Methane

Methane is a greenhouse gas that is approximately 21 times stronger than carbon dioxide and is emitted from numerous sources in the United States. The four largest sources of methane are enteric fermentation in domestic animals, landfills, natural gas systems, and coal mining. Since 1990, emissions of methane have decreased 5 percent in the United States.



Perfluorocarbons (PFCs)

A family of synthetic fluorinated chemicals, PFCs are used in semiconductor manufacture and also emitted during the electrolysis phase of aluminum production. PFCs generally have long atmospheric lifetimes as well as very high global warming potentials, so that even though they are emitted in relatively small quantities, their global warming impact is significant. Since 1990, PFC emissions have decreased 64 percent.

Carbon Dioxide: Industrial Processes

Some industrial processes emit carbon dioxide as part of the process itself rather than from energy inputs. The two largest industrial emitters of carbon dioxide are iron and steel production and cement production, each accounting for 1 percent of all carbon dioxide emissions in 2007. Industrial emissions of this gas have decreased 11 percent since 1990.

Nitrous Oxide

Nitrous oxide is approximately 310 times stronger than carbon dioxide at trapping heat, and is emitted from a variety of sources. In the United States, the largest source of this gas is agricultural soil management, responsible for approximately 67 percent of nitrous oxide emissions. Other significant sources include mobile and stationary combustion, adipic acid production, wastewater treatment, and manure management. Emissions of nitrous oxide have decreased 1 percent since 1990.

Carbon Dioxide: Fossil Fuel Combustion

Carbon dioxide is the most common and important greenhouse gas, and fossil fuel combustion is the largest source of carbon dioxide emissions in the United States, accounting for 80 percent of all emissions in 2007. In order of decreasing size, the contributors to these emissions were electricity generation, transportation, industry, and the residential and commercial sectors. Emissions from fossil fuel combustion have increased 22 percent since 1990.

Sulfur Hexafluoride

Sulfur hexafluoride is a very inert synthetic chemical with an extremely high global warming potential and a long atmospheric lifetime, giving it a greenhouse gas impact larger than its relatively small emissions would suggest. Because of its inert properties, it is used in electrical transmission and distribution as an insulator and interrupter, as a cover gas in magnesium production and processing, and in semiconductor manufacture. Emissions have decreased 50 percent since 1990.

Hydrofluorocarbons (HFCs)

HFCs are a class of synthetic chemicals used as alternatives to ozone depleting substances being phased out under the Montreal Protocol. These substitution uses include refrigeration and air conditioning, semiconductor manufacture, aerosols, and solvents. In addition, some is emitted during the production of another fluorochemical, HCFC-22. Emissions of this gas have increased 240 percent since 1990, mostly due to the phaseout of ozone depleting substances over that period. HFCs generally have high global warming potentials compared to the naturally occurring greenhouse gases (carbon dioxide, methane, and nitrous oxide).

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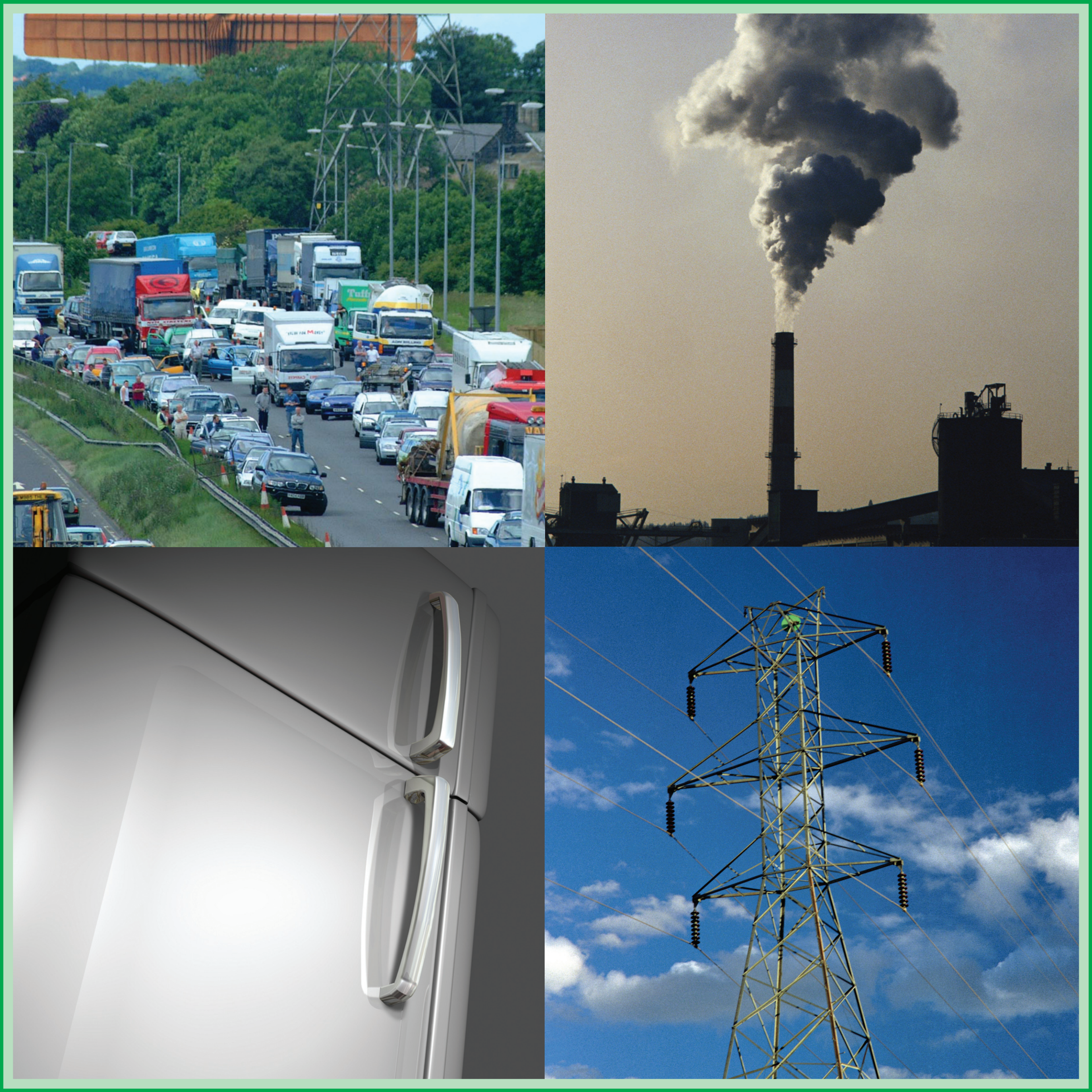

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